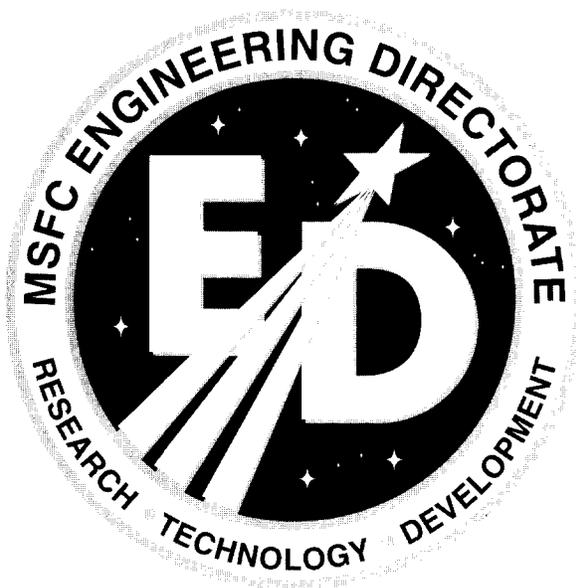




Simple Thermal Environment Model (STEM) User's Guide

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Preface

The development and verification of the NASA/MSFC Simple Thermal Environment Model (STEM) was sponsored by the Environments Group, Engineering Systems Department, Engineering Directorate of the NASA Marshall Space Flight Center. Technical questions concerning applications of the code and requests for copies of source code for STEM and TESTSTEM and their required data files may be addressed to:

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Symbols and Acronyms

A	effective radiating area of system (Section 2.1.1)
AU	astronomical unit - mean Earth-Sun distance
a	albedo at top-of-atmosphere (TOA, Section 1.3.5) or global-average albedo (Section 2.2.1)
a(0)	albedo at TOA, at solar zenith angle 0
a(θ)	albedo at TOA, at solar zenith angle θ
$\langle a \rangle$	orbital-average albedo at TOA (Section 2.3.2)
C_p	thermal specific heat capacity of system (Section 2.1.1)
c(θ)	albedo correction for solar zenith angle (Section 2.3.2)
$\langle c \rangle$	orbital average solar zenith angle correction (Section 2.3.2)
$\langle \cos(\theta) \rangle$	orbital average cosine solar zenith angle, equal to $\cos(\beta)/2$ (Section 3.1.2)
c_1 - c_4	coefficients for solar zenith angle albedo correction (Section 2.3.2)
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite
E_e	Earth-emitted longwave radiation, also known as OLR (Sections 1.3.6 and 2.2.1)
E_r	Earth-reflected shortwave radiation, or exitance (Section 1.3.5)
F_s	factor equal to 1 when in sunlight; 0 when in Earth's shadow (Section 4.1.2)
f_s	fraction of orbit in Earth's shadow (Section 1.3.9)
H	heat load input parameter (Section 2.1.2)
h	orbital altitude (Section 1.3.9)
i	orbital inclination, angle between orbital plane and equator (Sections 1.3.8 and 2.3.4)
LST	local solar time
LW	longwave (Section 1.3.2)
M	mass of system (Section 2.1.1)
MKS	meters-kilogram-seconds (equivalent to SI units)
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NFOV	narrow field of view
NOAA	National Oceanic and Atmospheric Administration
n	number of standard deviations for albedo or OLR (Section 2.3.3)
OLR	outgoing longwave radiation at TOA (Section 1.3.6)
P	orbital period
Q,Q(t)	time-varying heat load to system (Section 2.1.1)
Q	heat load per unit area (Section 4.3.2)
Q_0	orbital mean heat load (Section 2.1.1)
$Q_1(t)$	time-varying heat load perturbation about mean heat load (Section 2.1.1)
Q_1, Q_2	heat load per unit area (Section 4.3.2) for components 1 and 2
q	time-varying heat load per unit area (Section 4.1.2)
q_0	orbital average heat load per unit area (Section 3.1.2)
q_{ENV}	environmental heat load per unit area (Section 3.1.3)

Symbols and Acronyms (continued)

q_{int}	internal heat load per unit area (Section 3.1.2)
q_{S}	direct solar heat load per unit area (Section 3.1.2 or 4.1.2)
q_{SW}	shortwave heat load per unit area (Section 3.1.2 or 4.1.2)
q_{LW}	longwave heat load per unit area (Section 3.1.2 or 4.1.2)
R	seasonally-varying Earth-Sun distance in Astronomical Units (AU) (Section 1.2.2)
R_{s}	radius of spherical satellite (Section 2.1.1)
R_{o}	mean radius of solar disk (Section 1.3.1)
r	orbital radius (magnitude of Earth-center-satellite vector) (Section 3.1.2)
r_{e}	radius of Earth (may be approximated as 6378 km) (Section 3.1.2)
r_{30}	radius to top-of-atmosphere ($r_{\text{e}} + 30$ km) (Section 3.1.2)
S	direct-normal solar irradiance for Earth-orbiting satellite (Section 1.2.2)
S_{o}	direct-normal solar irradiance at 1AU, the solar constant (Section 1.2.1)
S_{cold}	design cold value for direct-normal solar irradiance (Section 1.2.3)
S_{hot}	design hot value for direct-normal solar irradiance (Section 1.2.3)
SD	standard deviation
SI	international system of units
STEM	Simple Thermal Environment Model
SW	shortwave (Section 1.3.2)
T, T(t)	time-varying temperature of satellite or satellite component (Section 2.1.1)
T_{H}	temperature magnitude parameter (Section 2.1.2)
T_{S}	characteristic blackbody temperature of Sun (Section 1.3.1)
T_{o}	orbital mean temperature (Section 2.1.1)
$T_1(t)$	time-varying temperature perturbation about mean temperature (Section 2.1.1)
T_1, T_2	temperature for components 1 and 2 (Section 4.3.2)
TESTSTEM	Test program for Simple Thermal Environment Model
TOA	top-of-atmosphere (Section 1.3.7)
UV	ultraviolet
WFOV	wide field of view
WMO	World Meteorological Organization
WRR	World Radiation Reference
WRC	World Radiation Commission
t	time
t_{avg}	averaging time (Section 2.3.3)
t_{S}	time period spent within Earth's shadow, per orbit (Section 1.3.9)
α	shortwave absorptance (also called absorptivity) (Sections 3.1.2 and 3.3.5)
β	minimum angle between orbital plane and Earth-Sun vector (Section 1.3.8)
δ	solar declination, minimum angle between equatorial plane and Earth-Sun vector (Section 1.3.8)
ϵ	longwave emittance (also called emissivity) (Sections 2.1.1 and 3.3.5)
θ	solar zenith angle (Sections 1.3.4 and 2.3.2)

Symbols and Acronyms (concluded)

σ	Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$)
σ_d	standard deviation in albedo or OLR (Section 2.3.3)
τ	thermal time constant (Sections 2.1.1 and 3.3.4)
φ	angular position around orbit, 0 nearest sub-solar point (Section 2.3.2)
ψ	phase angle for temperature response (Section 2.1.2)
ω	frequency of heat load input (Section 2.1.2)

1. Background

1.1 Scope and Purpose

This report is intended as a companion and technical supplement to Anderson et al. (2001), "Guidelines for the Selection of Near-Earth Thermal Environment Parameters for Spacecraft Design". It is the complete user's guide for the Simple Thermal Environment Model (STEM) and provides additional technical details not available in Anderson et al. (2001). The thermal environment of a satellite, in the context of STEM and these reports, consists of three components: (1) direct solar radiation (Section 1.2), (2) Earth-atmosphere-reflected shortwave radiation, as characterized by Earth's albedo (Section 1.3.5), and (3) Earth-atmosphere-emitted outgoing longwave radiation (OLR, Section 1.3.6). Optionally, STEM can also address effects of internal heat load, where appropriate. These reports provide guidelines and methodology for selecting "design points" for thermal environment parameters for satellites and spacecraft systems. The methods and models reported here are outgrowths of Earth Radiation Budget Experiment (ERBE) satellite data analysis and thermal environment specifications discussed by Anderson and Smith (1994). In large part, this report is intended to update (and supersede) those results.

A secondary purpose for this report is to furnish a handbook for satellite thermal environments, describing all Earth-related factors that influence thermal environments of satellites. As such, this is intended to be a "thermal environments handbook", not a "thermal engineering handbook". Thus, this report describes what parameters affect direct solar irradiance, albedo and OLR, and illustrates how to use STEM to obtain estimates of these values for use in thermal engineering analysis codes. The report is not intended to describe how to perform satellite thermal analysis using such thermal engineering codes.

Section 1 gives general background information, definitions of terms, and basic concepts. Section 2 discusses analysis of various effects on albedo and OLR, as measured by ERBE, that formed the basis for Anderson et al. (2001) and STEM development. Section 2 also describes the design of analysis procedures used in STEM and an associated time-series, simplified thermal analysis program (TESTSTEM). Sections 3 and 4 illustrate how to run STEM and TESTSTEM programs and interpret their results. Section 5 provides conclusions and answers to a set of "frequently-asked-questions" about STEM and TESTSTEM. Readers well versed in background concepts of thermal environments and analysis may prefer to proceed directly to the "users guide" sections (3 and 4), referring to Sections 1, 2, and 5 only as necessary.

1.2 Solar Constant and Orbital (Time of Year) Variations

1.2.1 Solar Constant “Solar constant” is direct-normal irradiance received from the Sun at average Earth-Sun distance of 1 Astronomical Unit (1 AU). For several years the NASA design standard solar constant (NASA, 1971; ASTM, 1973) was 1353 W/m^2 , based on the 1956 International Pyrheliometer Scale and solar spectral irradiance measurements summarized by Drummond and Thekaekara (1973).

As discussed by Iqbal (1983, Section 3.4), the World Meteorological Organization (WMO) has adopted a new radiometer scale, called the World Radiometric Reference (WRR), based on a data set of over 25000 absolute radiometric measurements maintained at the World Radiation Center (WRC) in Davos, Switzerland. Based on the WRR scale, WRC summarized eight solar constant measurements made from 1969 to 1980 and recommended (Fröhlich and Brusa, 1981; Fröhlich and Wehrli, 1981) a solar constant of

$$S_0 = 1367 \text{ W/m}^2 \quad (1.1)$$

This value has a standard deviation of 1.6 W/m^2 (0.12 percent) and a largest deviation (among values averaged) of $\pm 7 \text{ W/m}^2$ (0.5 percent). For meteorological purposes, this WRC solar constant was adopted in 1981 by the Commission for Instruments and Methods of Observation of the WMO. This WRC/WMO value is used in this report.

Recent satellite observations have indicated no need to revise the WRC/WMO solar constant. Figure 1 of Clawson (1991) shows about ± 0.3 percent (4 W/m^2) variation among three satellite systems (Nimbus 7, SMM/ACRIM I, and ERBS) measuring solar constants. Of these, the one thought to be most accurate (SMM/ACRIM, an active cavity radiometer) averaged about 1367.5 W/m^2 over 1980-1990 (Clawson, 1991). Variations of solar constant as solar activity changes during the solar cycle are approximately ± 0.05 percent (0.7 W/m^2). For example, Kuhn et al. (1988) show that solar-activity-induced decreases in solar constant (about -0.03 percent per year) during the early 1980s (Fröhlich, 1987) were generally offset by increases (about +0.02 percent per year) in the late 1980's. Changes due to short term (less than a year) and long term (many years) variations in solar activity are also minimal (Fröhlich, 1987; Schatten, 1988). For example, from his model for dependence of solar activity on sunspot number, Schatten estimates a change in solar constant of only about 1 W/m^2 between the 17th and late 20th centuries.

1.2.2 Orbital (Time of Year) Variations Direct normal irradiance received from the Sun, S , varies inversely with square of Earth-Sun distance, i.e.,

$$S = S_0 / R^2 \quad (1.2)$$

where S_0 is solar constant (1367 W/m^2) and R is Earth-Sun distance, measured in AU. Due to eccentricity of Earth's orbit ($e = 0.0167$), S varies from a minimum of $S_0/(1 + e)^2 = 1322 \text{ W/m}^2$ at aphelion (approximately July 4), to a maximum of $S_0/(1 - e)^2 = 1414 \text{ W/m}^2$ at perihelion (approximately January 3). Note that perihelion and aphelion are not coincident with summer and winter solstices, as stated on page 11 of Clawson (1991).

1.2.3 Design Hot and Cold Values for Direct Solar Irradiance Because of launch schedule changes and other mission uncertainties, thermal design usually is not based on solar irradiance for a specific time of year. Typical practice is to use design hot and design cold values that encompass the largest expected range of irradiance values. To allow for measurement uncertainty in solar constant and uncertainties introduced by solar activity and other variations (Section 1.2.1), STEM uses design hot and design cold values (S_{hot} and S_{cold}) that are input by the user. Thus, if the user decides that (consistent with Nimbus-7 and ERBE satellite observations) these uncertainties are in the range of $\pm 5 \text{ W/m}^2$ above and below the seasonal maximum and minimum values (given in the previous section), then design hot and cold values of

$$S_{\text{hot}} = 1414 + 5 = 1419 \text{ W/m}^2 \quad (1.3)$$

and

$$S_{\text{cold}} = 1322 - 5 = 1317 \text{ W/m}^2 \quad (1.4)$$

might be used. These values differ slightly from those used by Anderson and Smith (1994), who assumed a solar constant of 1371 W/m^2 , based on early Nimbus-7 satellite data, and an uncertainty range of $\pm 10 \text{ W/m}^2$.

1.3 Definitions of Other Thermal Environment Factors

1.3.1 Characteristic Blackbody Temperature of the Sun The characteristic blackbody temperature of the Sun, T_S , corresponding to direct solar irradiance S_0 , received at a distance of 1 AU from the Sun, is computed by the Stefan-Boltzmann relation, namely,

$$T_S = [S_0 / (R_0^2 \sigma)]^{1/4} \quad (1.5)$$

where σ is Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$) and R_0 is mean radius of the solar disk ($4.6523 \times 10^{-3} \text{ AU}$). $S_0 = 1367 \text{ W/m}^2$ yields a characteristic blackbody temperature $T_S = 5777 \text{ K}$. This value differs slightly from that given in Table 9-1 of Anderson and Smith (1994) (5762 K consistent with a solar constant of 1353 W/m^2).

1.3.2 Spectral Distribution of Radiation The characteristic blackbody temperature of the Sun determines the spectral distribution of both incoming radiation received from the Sun and radiation reflected by the Earth-atmosphere system. This spectral distribution peaks at a wavelength near $0.5 \mu\text{m}$. Radiation emitted thermally by the Earth-atmosphere system has a spectral distribution characterized by terrestrial temperatures (at most about 320 K). This distribution peaks at wavelengths near $10 \mu\text{m}$. Because of characteristics of blackbody distributions, the Earth-atmosphere system emits very little thermal radiation at wavelengths below about $3 \mu\text{m}$. Incoming and reflected solar radiation is referred to as shortwave (SW), i.e., wavelengths shorter than about $3 \mu\text{m}$. Radiation emitted thermally by the Earth-atmosphere system is referred to as longwave (LW), i.e., wavelengths longer than about $3 \mu\text{m}$.

Note that the shortwave (solar) spectrum is sometimes erroneously referred to as ultraviolet (UV) radiation [Costello and Costello (1995)]. The solar spectrum actually consists of UV ($< 0.4 \mu\text{m}$), visible (0.4 to $0.7 \mu\text{m}$), and near infrared (0.7 to $\approx 3 \mu\text{m}$) wavelengths.

1.3.3 Characteristic Blackbody Temperature of Space Frequently the characteristic blackbody temperature of space is taken as 0 K in thermal analysis. However, microwave measurements of cosmic background radiation indicate an approximately uniform irradiance with a blackbody temperature of about 3 K. For thermal analysis purposes, differences between blackbody temperatures of 3 K and 0 K are usually negligible.

1.3.4 Solar Zenith Angle At any location on Earth, solar zenith angle, θ , is the angle between two vectors: (1) the vector from Earth's center to the given location, and (2) the vector from Earth's center to the Sun (or Earth-Sun vector). Solar zenith angle for a satellite at a given position is thus defined as the angle between the Earth-satellite vector and the Earth-Sun vector. Geometry defining solar zenith angle is illustrated in Figure 1.1. Solar zenith angles for a satellite range from 0 (for Sun at zenith) to 180° (for Sun at nadir). In STEM, albedo corrections for solar zenith angle effects are done by a process discussed in section 2.3.2.

1.3.5 Albedo The general term albedo refers to the ratio of reflected (or scattered) radiation to irradiance received from the Sun. As used in this report, albedo is more precisely defined as the "local" albedo of a small section of the top-of-atmosphere. Top-of-atmosphere (TOA) is defined in Section 1.3.7. Differences in definition between local albedo and other quantities such as Bond albedo and geometric albedo are discussed on pages 9 and 10 of Clawson (1991). Albedo may also be defined as a function of wavelength (spectral albedo) or integrated over the shortwave range of wavelengths (bolometric albedo). In this report only local, bolometric albedo is considered.

Local solar irradiance received at TOA is $S \cos(\theta)$, where S is direct normal solar irradiance (Section 1.2) and θ is solar zenith angle (Section 1.3.4). Reflected or scattered radiation (exitance, E_r) for a small section at TOA is determined by integration of

radiances reflected from Earth's surface or scattered from atmosphere or clouds and received at TOA (from all parts of Earth's surface and atmosphere within the field of view, looking downward from TOA). Thus, albedo, a , is

$$a = E_r / [S \cos(\theta)] \quad (1.6)$$

1.3.6 Outgoing Longwave Radiation (OLR) Outgoing longwave radiation (OLR) is longwave radiation emitted thermally (emitted exitance, E_e) by the Earth-atmosphere system, evaluated at top-of-atmosphere (Section 1.3.7). OLR has contributions that were emitted by Earth's surface and atmospheric components, including clouds. Emitted radiation comes from sources at a range of terrestrial temperatures. It is modified by absorption processes that take place within atmospheric layers of varying temperatures. Spectrally, OLR consists of wavelengths longer than about $3 \mu\text{m}$ (Section 1.3.2). Only broad-band OLR (spectral OLR integrated over all long wavelengths) is considered in this report.

1.3.7 Top-of-Atmosphere (TOA) Top-of-atmosphere, a hypothetical surface, is above the level at which significant contributions are made by the atmosphere to either reflected (albedo) or emitted (OLR) radiation. From a practical standpoint, TOA may be taken as 30 km above Earth's surface. If reflected and emitted radiances come from spatially-homogeneous sources and are angularly uniform (Lambertian sources), then radiation above TOA would vary inversely with square of radius from Earth's center. This is a simplifying assumption within STEM. However, true spatial homogeneity and angular uniformity are not prevalent for either reflected or emitted components of Earth radiation. Earth Radiation Budget Experiment data (Section 1.4) used to develop STEM were converted from satellite altitude to TOA by a process described by Smith and Green (1981). In STEM, conversion from TOA back to any satellite altitude is done by a simplified process discussed in Section 3.1.2.

1.3.8 Beta Angle Orbital beta angle is defined as the minimum angle between the orbital plane and the Earth-Sun vector. Depending on orbital inclination, beta can take on values within the range ± 90 degrees. For many purposes, however, it is necessary to consider only the magnitude of beta (not its sign). This is because differences between positive and negative beta have to do solely with whether the satellite appears to move in its orbit clockwise or counter-clockwise when viewed from the perspective of the Sun. Once during each orbit a satellite will be in the plane defined by the Earth-Sun vector and the perpendicular to the orbit and also on the sunward side of its orbit. At such a point, the satellite will experience its minimum solar zenith angle for the orbit. This solar zenith angle will equal the magnitude of the beta angle. Thus, we may also interpret beta via the relationship

$$|\beta| \leq \theta \quad (1.7)$$

i.e., the magnitude of beta is equal to the minimum solar zenith angle for a given orbit. Chapter 2 of Gilmore (1994) provides further discussion of beta angle, including an equation to compute beta from satellite orbital parameters and solar position .

In general, as solar declination, δ , changes with season and as a satellite orbit precesses, the beta angle will take on values over the range $\pm (i + 23.45 \text{ degrees})$, where i is inclination of the orbit. For example, a satellite whose orbit is in the equatorial plane ($i = 0$) has beta angles equal to δ (which varies over $\pm 23.45 \text{ degrees}$). There are, however, exceptions to this rule. For example, satellites in Sun-synchronous, noon-midnight, polar orbits (approximate orbit of ERBE NOAA-9, $i \approx 99 \text{ degrees}$) would have small beta angles (because the orbital plane remains close to the direction of the Earth-Sun vector).

1.3.9 Orbital Shadow Time As seen by an observer on the Earth's surface, geometrical sunrise or sunset occurs when the solar zenith angle, θ , is equal to 90 degrees (Figure 1.1). Neglecting effects such as refraction and atmospheric scattering, a point on the Earth's surface will be in darkness when $\theta > 90 \text{ degrees}$. A satellite in circular orbit will be in Earth's shadow only when two conditions are met: $\theta > 90 \text{ degrees}$, and

$$r \sin(\theta) < r_e \quad (1.8)$$

where r_e is Earth's radius, and r is the circular orbit radius. Simple geometric considerations (e.g., Section 5-5 of Kreith, 1962) show a satellite will be in Earth's shadow for a time period

$$t_s = (P / \pi) \cos^{-1} \{ [1 - (r_e / r)^2]^{1/2} / \cos(\beta) \} \quad (1.9)$$

each orbit, where P is orbital period. Equation 1.9 is equivalent to, but simpler than the expression given by Kreith (who uses angle $\tau = 90 \text{ degrees} - \beta$, among other differences). Thus, the fraction of each (circular) orbit spent in Earth's shadow is

$$f_s = (1 / \pi) \cos^{-1} \{ [1 - (r_e / r)^2]^{1/2} / \cos(\beta) \} \quad (1.10)$$

Figure 1.2 shows variations of shadow fraction, f_s , with beta angle and orbital altitude, h , where $h = r - r_e$.

1.4 Earth Radiation Budget Experiment (ERBE) Satellite Characteristics

Data used to define thermal environment parameters in STEM are from the Earth Radiation Budget Experiment (Barkstrom and Smith, 1986). The ERBE program consists of three satellites, a Sun-synchronous satellite (NOAA-9, altitude 849 km, $i = 99$ degrees) in an orbit with equator crossing times 0230 and 1430 local solar time (LST), a Sun-synchronous satellite (NOAA-10, altitude 815 km, $i = 99$ degrees) with 0730 and 1930 LST equator crossing times, and a precessing orbiter [Earth Radiation Budget Satellite (ERBS), altitude 610 km, $i = 56$ degrees], that observes at varying local solar times.

The ERBE instrument package on each of these satellites collects Earth-viewing radiation data from both narrow-field-of-view (NFOV), scanning instruments and wide-field-of-view (WFOV) active cavity radiometers. Data from WFOV instruments are the basis for the guidelines (Anderson et al., 2001) and STEM development because they measure more directly the shortwave and longwave irradiances that affect spacecraft surfaces. S-7 ERBE WFOV data were used that consist of 16-second time-averaged shortwave and longwave irradiances converted to top-of-atmosphere (Section 1.3.7). Barkstrom et al. (1989) give a description of ERBE instruments, archival data sets, procedures for instrument calibration, and data validation. ERBE WFOV active cavity radiometer data are expected to be more accurate than the earlier, passive flat-plate radiometers flown on Nimbus-7. Bess and Smith (1993) give a comparison of results from Nimbus-7, NOAA-9 ERBE, and ERBS.

Development of the guidelines (Anderson et al., 2001) and STEM methodology is based on 28 monthly data sets of S-7 ERBE WFOV 16-second resolution data. Fourteen months of these data are from ERBS (spanning November 1984 through November 1986), one month from NOAA-10 (July 1987), and thirteen months from NOAA-9 ERBE (spanning February 1985 through July 1987). All seasons are represented (five winter, eight spring, nine summer, six fall months) in the data sets.

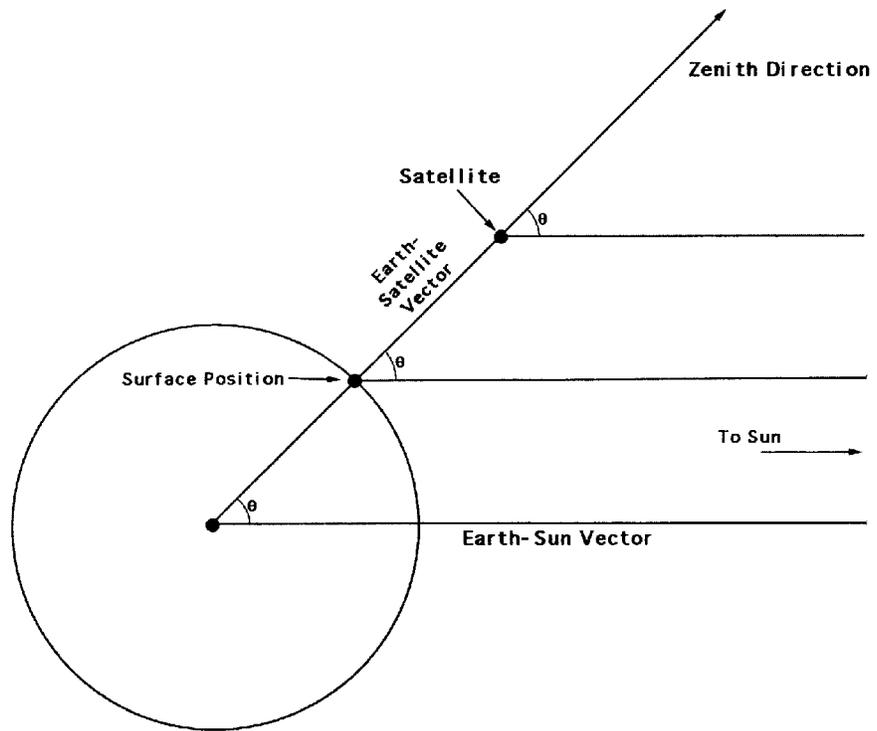


Figure 1.1 Illustration of solar zenith angle, θ , the angle between the Earth satellite vector and the Earth-Sun vector.

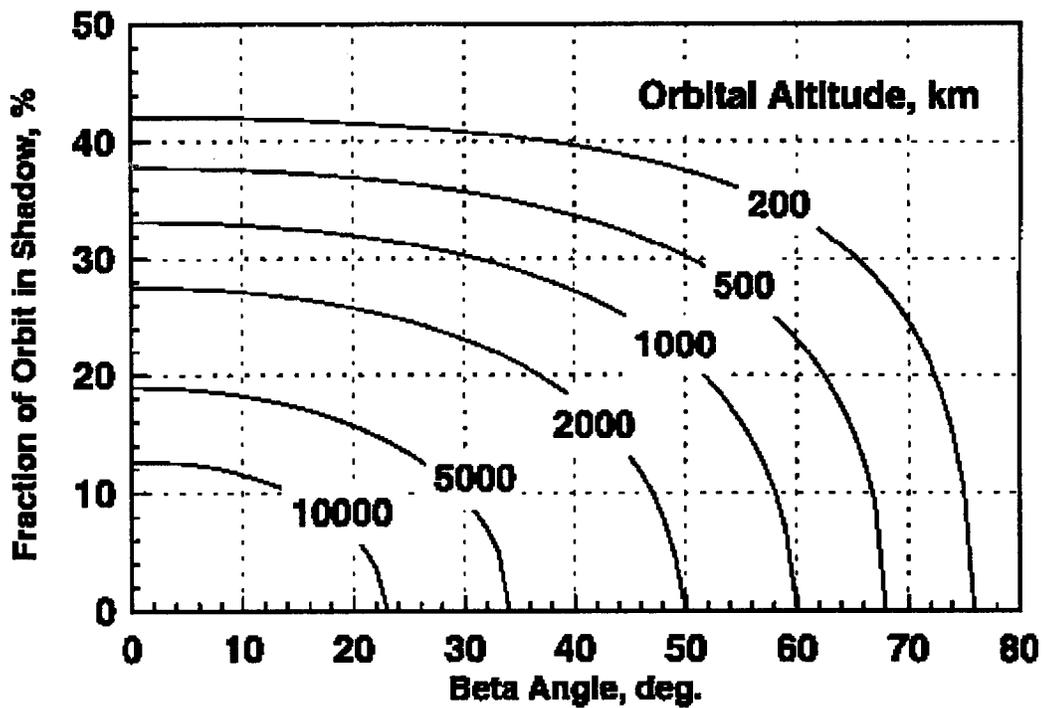


Figure 1.2 Fraction of orbit in Earth's shadow, f_s , from Equation (1.10), as a function of orbital beta angle and altitude

2. Development of Methodologies

2.1 Thermal Time Constant

2.1.1 Definition of Spacecraft System Thermal Time Constant Thermal time constant, τ , for a spacecraft system can best be defined in terms of a simplified, linearized equation for variations of temperature, T , of the system. Let

$$M C_p \frac{dT}{dt} = Q - A \varepsilon \sigma T^4 \quad (2.1)$$

where M is system mass, C_p is system specific heat capacity, Q is total heat load, consisting of net shortwave irradiance (direct solar plus Earth-reflected albedo components plus shortwave reflected from any other satellite systems) plus longwave irradiance received by the system (Earth-emitted plus longwave received from any other satellite systems) plus any internal heat load experienced by the system, A is effective area of the system (e.g., $4 \pi R_s^2$ for a spherical satellite of radius R_s), ε is longwave emittance of the system, and σ is Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). Further, let time variation of temperature T and total heat load, Q , be given by

$$T(t) = T_0 + T_1(t) \quad (2.2)$$

$$Q(t) = Q_0 + Q_1(t) \quad (2.3)$$

where T_0 and Q_0 are orbital averages of temperature and total heat load, and T_1 and Q_1 are temperature and heat load perturbations about their respective average values. Note, since T_0 and Q_0 are orbital average values, $dT_0/dt = 0$ and $dQ_0/dt = 0$.

Substitution of Equations 2.2 and 2.3 into 2.1, along with the linearizing assumption $(T_0 + T_1)^4 \approx T_0^4 + 4 T_0^3 T_1$, yields

$$Q_0 = A \varepsilon \sigma T_0^4 \quad (2.4)$$

$$M C_p \frac{dT_1}{dt} = Q_1(t) - 4 A \varepsilon \sigma T_0^3 T_1(t) \quad (2.5)$$

Equation 2.5 has the general solution for time variation of temperature perturbations

$$T_1(t) = e^{-t/\tau} \left\{ T_1(0) + (M C_p)^{-1} \int_0^t Q_1(t') e^{t'/\tau} dt' \right\} \quad (2.6)$$

where $T_1(0)$ is perturbation temperature at arbitrary starting time, 0, and time constant, τ , which defines the exponential time variation of T_1

$$\tau = M C_p / (4 A \varepsilon \sigma T_0^3) = M C_p T_0 / (4 Q_0) \quad (2.7)$$

Equation 2.7 shows that system time constant is proportional to system mass and inversely proportional to the cube of average temperature, T_0 ; system time constant is also inversely proportional to average heat load, Q_0 .

2.1.2 Effects of Time Constant on Temperature Variations Effects of time constant on temperature are illustrated by solutions to Equation 2.5 via Equation 2.6 for two simplified examples. In the first, consider a step function heat load perturbation $Q_1(t) = 0$ for $t < 0$ and $Q_1(t) = H$ (H is a constant) for $t \geq 0$. With an assumption that initial temperature perturbation is zero ($T_1(0) = 0$), resulting time behavior of T_1 is

$$T_1(t) = T_H (1 - e^{-t/\tau}) \quad (2.8)$$

where ultimate temperature response, T_H , is

$$T_H = H \tau / (M C_p) = H / (4 A \varepsilon \sigma T_0^3) = H T_0 / (4 Q_0) \quad (2.9)$$

Note, temperature perturbation response magnitude, T_H , is positive or negative depending on whether radiative heat load perturbation, H , is positive or negative (i.e., whether perturbed radiative heat load is larger or smaller than average radiative heat load, Q_0). From Equation 2.9, the ultimate fractional change in temperature, T_H / T_0 , is one fourth the fractional change in radiative heat load, H / Q_0 . Time constant, τ , characterizes the exponential variation with time between initial, 0, and final, T_H , temperature perturbation values.

In the second example, radiative heat load perturbation is sinusoidal with time

$$Q_1(t) = H \sin(\omega t) \quad (2.10)$$

and started at some time in the distant past. The solution from Equation 2.6 under these assumptions (all effects of initial conditions have diminished to zero) is

$$T_1(t) = T_H \cos(\psi) \sin(\omega t - \psi) \quad (2.11)$$

where ψ , the phase lag angle between imposed heat load, $Q_1(t)$, and temperature response, $T_1(t)$, is given by

$$\cos(\psi) = 1 / [1 + (\omega \tau)^2]^{1/2} \quad (2.12)$$

For all frequencies, ω , the frequency of temperature response is the same as frequency of radiative heat load perturbation imposed. For low frequency heat load perturbations ($\omega \tau \ll 1$; $\cos(\psi) \approx 1$), almost no time lag exists between heat load perturbation and temperature response, and temperature response amplitude is approximately T_H (Equation 2.9). For high frequency heat load perturbations ($\omega \tau \gg 1$ and $\cos(\psi) \approx 1 / (\omega \tau)$), temperature response lags heat load perturbation by about 90 degrees, and the amplitude of temperature response is small (approximately $T_H / (\omega \tau)$).

More realistic effects of time constant are illustrated in Figure 2.1, which shows numerical solutions to Equation 2.1 for spherical satellites having different time constant values and encountering the same temporal variations of radiative heat load from direct solar, albedo, and OLR components in low Earth orbit. Considerable smoothing of the time variation of temperature is illustrated as the value of time constant is increased. Figure 2.1 also shows that temperature extremes (maximum or minimum values) vary from orbit to orbit regardless of time constant value. However, range between extreme values (maximum-to-minimum) is smaller for large time constant values than for small. There is also less orbit-to-orbit variability in temperature extremes for large time constant values than for small values.

2.2 Earth-Related Effects on Thermal Environments

2.2.1 Global Radiation Balance Global, annual-average conditions for Earth are very nearly in radiative energy balance. Such a balance is achieved when net absorbed, global-average, shortwave radiation received from the Sun is balanced by global-average, outgoing longwave radiation (OLR) emitted by the Earth-atmosphere system. On a global-average basis, Earth receives solar energy at a rate given by solar constant, S_0 , over Earth's circular cross-sectional area, πr_e^2 , where r_e is Earth's radius. Of the amount received, a fraction $(1 - a)$ is absorbed; a is global-average albedo. Balance is achieved

when emitted exitance (OLR), E_e (emitted over the spherical area $4 \pi r_e^2$), is determined by

$$4 \pi r_e^2 E_e = S_0 (1 - a) \pi r_e^2 \quad (2.13)$$

or

$$E_e = \frac{1}{4} S_0 (1 - a) \quad (2.14)$$

For $S_0 = 1367 \text{ W/m}^2$ and global-average albedo, $a = 0.30$, this implies a global average OLR of $E_e = 239 \text{ W/m}^2$. Note, Earth, like any spherical body that receives radiation from a single direction (the Sun), has a radiative form factor of $\frac{1}{4}$.

Although this radiative balance applies on a global, annual-average basis, many factors create departures from radiative balance on local and regional scales. These factors include energy storage and horizontal transport by the oceans and atmosphere. Conditions of albedo and OLR encountered by a satellite at any given time are expected to depart significantly from these global balance conditions. Some of these effects are discussed more fully in Section 2.2.2 and 2.2.3.

Global-average radiative balance, via Equation 2.14, for ERBE ERBS data is illustrated by the unnumbered table on page 6 of Costello and Costello (1995), $a = 0.299$ and $E_e = 240 \text{ W/m}^2$. ERBE NOAA polar orbiting satellite data in this table do not satisfy Equation 2.14 ($a = 0.361$, $E_e = 233 \text{ W/m}^2$, see note by Costello and Costello, page 2), because (unlike ERBS) ERBE polar orbiting satellites sample only a limited range of local solar times. Global mean values from the unnumbered table in Section IIa of Clawson (1991), $a = 0.30$ and $E_e = 234 \text{ W/m}^2$, are also not in radiative balance. However, conditions of radiative balance exist within the limits of uncertainty in global mean albedo (± 0.01) and OLR ($\pm 7 \text{ W/m}^2$) given by Clawson.

2.2.2 Effects of Earth Surface and Atmosphere Figure 2.2 illustrates a contour plot derived from frequency of observed ERBE (ERBS, medium inclination orbit) albedo and OLR. All albedo values in the figure were corrected to solar zenith angle 0 (Sections 2.2.3 and 2.3.2). In this figure, ERBS data were averaged over 128 seconds, along the orbital path, before binning averages into intervals (“boxes”) of width 1 W/m^2 on the OLR axis and height 0.01 on the albedo axis. Total number of averaged observations represented in this figure is 132941. The highest number density (data points observed in any one box) was 151 (at $\text{OLR} = 270 \text{ W/m}^2$ and albedo $a = 0.12$). Within constraints imposed by the contour plotting program, no data points occurred outside the contour labeled 1 in Figure 2.2 (note the “spike” in the upper left of this diagram is an artifact of the contouring plotting program). Only daytime data from ERBS are plotted in Figure 2.2 (albedo is defined as zero for nighttime periods).

During 128 seconds, ERBS traverses about 8.5 degrees of latitude-longitude (about 950 km of ground-track distance). Highest density of observations is near the lower right

of Figure 2.2, for cases when the satellite is viewing relatively cloud-free parts of Earth over either ocean or vegetated land. These are areas with rather high temperature (large OLR values), but which are relatively dark (low albedo values). A secondary maximum of data density occurs in the upper left region of Figure 2.2. Data here are for cases when the satellite is viewing cloudy regions or relatively cloud-free areas with snow or ice on the surface. These areas are low temperature (low OLR) but bright (high albedo). A region of high OLR and intermediate-to-high albedo in Figure 2.2 is associated with relatively cloud-free desert areas (high daytime temperature with high albedo).

2.2.3 Effects of Solar Zenith Angle and Latitude If top-of-atmosphere (TOA) direct normal solar irradiance (i.e. irradiance on a satellite surface oriented perpendicular to the Earth-Sun vector) is S , then irradiance on a local horizontal surface (e.g., a satellite surface oriented perpendicular to the Earth-satellite vector) at TOA is $S \cos(\theta)$, where θ is solar zenith angle at satellite position. Earth-reflected shortwave irradiance (or shortwave exitance, E_r) at TOA is given by Equation 1.6 and

$$E_r = a(\theta) S \cos(\theta) \quad (2.15)$$

where $a(\theta)$ is solar-zenith-angle-dependent albedo.

In most cases, albedo is lowest for overhead Sun ($\theta = 0$) and increases monotonically as θ increases. One reason for this albedo behavior is a characteristic of inhomogeneous cloud fields. If a satellite views a partly cloudy area (or overcast cloud having non-uniform spatial structure) when the Sun is overhead, then sunlight can more effectively penetrate to (and be reflected from) the underlying (darker) surface (ocean or land surface, or thinner, less reflective, parts of the cloud field). When the Sun is at a higher zenith angle (lower elevation angle), sunlight penetrates less effectively and is reflected mostly from bright, upper surfaces of the cloud field. Note the opposite effect (albedo decreasing with increasing zenith angle) occurs when the viewed area is a patchy forest of dark (low albedo) trees growing over bright (high albedo) soil. The latter example, however, occurs infrequently and has very little impact on global or regional average albedo.

Another reason albedo increases with zenith angle is path-length effects in a cloud-free atmosphere. For near-overhead Sun, the sunlight path through the atmosphere is relatively short and makes a relatively small contribution to TOA exitance from atmospheric scattering. For high solar zenith angles the sunlight path through the atmosphere is long with significant contribution from atmospheric scattering to TOA exitance.

Latitude has a direct effect on both albedo and OLR. Higher latitudes have colder temperatures that cause lower OLR values. Higher latitudes also have more frequent snow and ice that cause higher albedo values. There is also an indirect effect of latitude on albedo. At high latitudes the Sun can never be near overhead and solar zenith angle

cannot be small. Hence, high latitude albedo, even from a dark surface type, tends to be large because albedo is greater at high solar zenith angles.

2.3 Effects of Various Factors on ERBE Albedo and OLR

2.3.1 Sensitivity Study of ERBE Albedo and OLR Data First step in the development of STEM was to review and extend the sensitivity studies conducted by Anderson and Smith (1994) of effects of various parameters on albedo and OLR observed by ERBE (ERBS and NOAA satellites). The concept was to base STEM on tables of hot (maximum) and cold (minimum) environmental irradiances from direct, albedo, and OLR components, with hot/cold values binned by appropriate ranges of relevant parameters. Candidate parameters for data bins are: (1) solar zenith angle, (2) orbital beta angle, (3) latitude or orbital inclination, (4) thermal time constants of the system or averaging time for irradiances, (5) season or month, (6) time of day, and (7) probability of encountering a given set of irradiance values. Explicit inclusion of all parameters in STEM would render the model too complicated for most thermal engineering applications. Furthermore, while some candidate parameters have significant effect and warrant inclusion in the model, others have only marginal effect and can be ignored or treated simply in the model.

Results of the sensitivity study, described in this section, provide justification for the assumptions made in STEM. Subsections describe several parameters analyzed in the sensitivity study and provide justification for whether effects of each parameter are explicitly included, treated simply, or ignored.

2.3.2 Solar Zenith Angle Corrections Section 2.2.3 discussed that albedo tends to increase with increasing solar zenith angle. ERBE observes actual (solar-zenith-angle dependent) albedo energy fluxes at the satellite, at a given ground location and time. For a uniform database, e.g., to compute appropriate time averages, ERBE albedo observations are converted to equivalent top-of-atmosphere (TOA) albedo at solar zenith angle zero. This conversion is performed using the satellite view factor correction to TOA from Green and Smith (1991) and the empirical ERBE albedo correction term $c(\theta)$, given in Anderson and Smith (1994) and

$$c(\theta) = c_1 \theta + c_2 \theta^2 + c_3 \theta^3 + c_4 \theta^4 \quad (2.16)$$

where (for θ in degrees), $c_1 = 1.3798 \times 10^{-3}$, $c_2 = -2.1793 \times 10^{-5}$, $c_3 = 6.0372 \times 10^{-8}$, and $c_4 = 4.9115 \times 10^{-9}$. Equation 2.16 is valid for $0 \leq \theta \leq 90$ degrees; $c(\theta)$ is defined as zero for $\theta > 90$ degrees. However, because of increasing uncertainty for large θ , its application in the final STEM and Anderson et al. (2001) results is limited to $0 \leq \theta \leq 65$.

This observed dependence of $c(\theta)$ on θ , illustrated in Figure 2.3, agrees very well with expected dependence on θ of TOA reflectance in a uniform atmosphere of

reasonable optical depth. See, for example, theoretically computed TOA reflectances in Liou (1980) Table 6.3 (optical depth 0.25).

ERBE-observed TOA albedo, $a(\theta)$, is converted to solar-zenith-angle-zero albedo, $a(0)$, by

$$a(0) = a(\theta) - c(\theta) \quad (2.17)$$

All analysis operations, such as time averaging, are performed on solar-zenith-angle-zero albedo values. In computational operations within STEM or TESTSTEM programs, when actual solar zenith angle is required, albedo is reconstructed by reverse process, namely

$$a(\theta) = a(0) + c(\theta) \quad (2.18)$$

One problem requiring solar zenith angle correction is defining an orbital-average albedo value, $\langle a \rangle$, to be used in thermal engineering analysis programs that assume albedo does not vary with solar zenith angle (i.e., programs that assume TOA exitance is given by $E_r = \langle a \rangle S \cos(\theta)$, rather than by Equation 2.15). For this purpose, we can compute $\langle a \rangle$ from a time average of $a(\theta)$ over orbital period, P ,

$$\langle a \rangle = \int_0^P a(\theta) \cos(\theta) dt / \int_0^P \cos(\theta) dt \quad (2.19)$$

Substitution of Equation 2.18 into 2.19 yields the result

$$\langle a \rangle = a(0) + \langle c \rangle \quad (2.20)$$

where orbital average correction term, $\langle c \rangle$, is defined by

$$\langle c \rangle = \int_0^P c(\theta) \cos(\theta) dt / \int_0^P \cos(\theta) dt \quad (2.21)$$

Simplify Equation 2.21 by using angular position around the orbit, φ , measured from zero at the most nearly sub-solar point and using the relation

$$\cos(\theta) = \cos(\beta) \cos(\varphi) \quad (2.22)$$

where, for a circular orbit, φ increases linearly with time

$$\langle c \rangle = \frac{1}{2} \int_{-\pi/2}^{\pi/2} c(\theta) \cos(\varphi) d\varphi \quad (2.23)$$

Values of $\langle c \rangle$ depend on orbital beta angle, as illustrated in Table 2.1. This table also gives short-term albedo correction at minimum solar zenith angle ($\theta_{\min} = \beta$), computed from Equation (2.16).

Table 2.1 - Values of orbital-average albedo correction term, $\langle c \rangle$, computed numerically from Equation 2.21, and short-term albedo correction at minimum solar zenith angle, $c(\beta)$.

Orbital Beta Angle (°)	Orbital Average Albedo Correction $\langle c \rangle$	Correction at Min. Solar ZA, $c(\beta)$
0	0.04	0.01
10	0.04	0.01
20	0.05	0.02
30	0.06	0.03
40	0.07	0.04
50	0.09	0.05
60	0.12	0.08
70	0.16	0.13
80	0.22	0.20
90	0.31	0.31

2.3.3 Recurrence Frequency, Averaging Time, and Thermal Risk Highest resolution ERBE data used in this study represent averages of albedo and OLR over 16 seconds of satellite orbit. The Anderson and Smith (1994) study considered running mean (time-overlapped) averages over 10 additional averaging times from 64 to 5400-seconds.

Effects of thermal time constant on satellite temperature response can be accounted for if appropriate averaging times are used for albedo/OLR statistics. From detailed studies of temperature response to varying time constants (Section 2.1.2), it was determined that the appropriate data averaging time, t_{avg} , to use for a given thermal time constant, τ , is to have t_{avg} within the range from roughly $\tau/4$ to approximately τ . If t_{avg} much less than $\tau/4$ is used, then temporal variations in heat load are represented that are more variable than temperature responses that can result from the (relatively large) thermal time constant. If t_{avg} much greater than τ is used, then variability of heat load is too smoothed compared with the amount of thermal response than can result from the (relatively small) thermal time constant. Considering this result, and the degree of variation of Anderson and Smith (1994) statistics with averaging time, the decision was to limit the number of averaging times used in STEM to seven (from 16 seconds to 24 hours). Note non-overlapping time averages are used for STEM statistics to make the resultant time statistics closer to those expected from uncorrelated time-series data, but comparison indicates no practical difference from the (time-overlapped) running means used by Anderson and Smith (1994).

Anderson and Smith (1994) present their statistical results as tables of percentile values for albedo and OLR versus averaging time. A percentile value gives probability (expressed as a percent) that a given value (of albedo or OLR) will not be exceeded. Thus, an observed albedo or OLR value will be equal to or less than the albedo or OLR associated with a given percentile value with a probability equal to the percentile. Percentile values evaluated by Anderson and Smith are 0.04, 1, 3, 5, 50, 95, 97, 99 and "maximum observed". In order to simplify user choices regarding thermal risk level and to minimize potential for confusion about risk, STEM provides two sets of statistics: one to be used for "mission critical" components and the other to be used for "non-critical" components. One potential area of confusion is that, because of non-linearity and other factors, a probability value for albedo and OLR does not convert to the same probability value for system extreme temperature. Another potential source of confusion concerns frequency of occurrence (or exceedance) versus mission-lifetime frequency of occurrence (or exceedance).

To illustrate application of non-critical and mission-critical statistics, consider two cases. For a non-critical system component, an engineer may be willing to accept a small percentage (say five percent) risk of temperatures exceeding an extreme hot level. Note, however, 90-minute values having a five percent frequency of occurrence would occur on average once every 1.25 days. Such a condition is likely unacceptable for mission-critical system components. For mission critical components, an engineer might accept at most a small (say five percent) risk of exceedance once during mission lifetime. A 90-minute value that occurs once during a one-year mission would have a frequency of 0.02

percent, while a five percent mission-lifetime probability for 90-minute values would be equivalent to an average occurrence of once in 20 years, or 0.0009 percent.

In an attempt to account for mission-lifetime extremes, Costello and Costello (1995) suggested using albedo or OLR values computed from mean $\pm n \sigma_d$, where n is as large as 6, and σ_d is standard deviation (albedo or OLR). For example, with $n = 5$, a 16 second value no larger than mean $+ 5 \sigma_d$ would occur, on average, once every 1.7 years (probability of not being exceeded = 0.9999997). A problem with this approach is that actual distributions of albedo or OLR are not Gaussian to this many standard deviations. For example, in the unnumbered table on page 6 of their paper, Costello and Costello give observed mean ERBS albedo as 0.299 with standard deviation 0.083. Thus, with n larger than 3.6, low albedo values (mean - $n \sigma_d$) go negative, a physical impossibility.

Indeed, there was not enough ERBE data available (section 1.4) for use in development of STEM to accurately evaluate long-mission-lifetime probabilities. The STEM mission critical environments provided (section 2.4) are nevertheless considered adequate for specifying albedo and OLR values. Thermal analysts need, however, to make their own decisions about what additional temperature safety margins need to be applied, since no specific "safety margin" has been applied to albedo and OLR values themselves.

2.3.4 Orbital Beta Angle, Latitude and Orbital Inclination One would expect orbital beta angle (defined in Section 1.3.8) to have a major effect on satellite thermal environments. For example, when $\beta = 0$ a satellite passes (once per orbit) over the sub-solar point, where solar zenith angle is 0 and reflected solar radiation tends to be largest (Equation 2.15). Warmest Earth-atmosphere temperatures and corresponding largest OLR values also tend to occur near the sub-solar point.

However, $\beta = 0$ can occur for a variety of orbital inclinations: for example, noon-midnight polar orbits, or equatorial orbits when solar declination is zero. Because range of latitudes covered by a satellite orbit is determined by its orbital inclination (Section 1.3.8) and latitude has a significant effect on albedo and OLR (Section 2.2.3), it is appropriate to examine relative effects of beta angle and latitude (orbital inclination) on albedo and OLR statistics.

Figure 2.4 gives a contour plot of mean ERBS albedo (corrected to solar zenith angle $\theta = 0$) as a function of beta angle and absolute value of latitude (i.e., north and south latitudes considered equally). This figure shows average albedo to vary only slightly with beta angle, but to vary significantly with latitude. For example, average albedo (at $\theta = 0$) is uniformly less than about 0.2 for latitudes equatorward of ± 25 degrees, as encountered in a low inclination orbit, while average albedo is uniformly greater than about 0.3 for latitudes poleward from about $\pm 55^\circ$. Note since albedo has been corrected to $\theta = 0$ in Figure 2.4, large albedo values at high latitudes are purely a latitude effect, having nothing to do with high solar zenith angle values that occur at high latitudes (Section 2.2.3). Figure 2.5, which shows maximum, median (50 percentile) and minimum albedo values (at solar zenith angle zero) for 16-second ERBS data, confirms that none of these statistics has a strong dependence on beta angle.

Figure 2.6 shows that average OLR also varies much more with latitude than with beta angle. In this figure, largest average OLR values ($\approx 260 \text{ W/m}^2$) occur near ± 20 degrees latitude, while slightly lower OLR values ($< 250 \text{ W/m}^2$) occur near the equator. Lower equatorial OLRs are due to influence of the intertropical convergence zone, a region of high (and therefore cold) convective clouds that occurs within a few degrees of the equator. In general, Figure 2.6 shows a progression of OLR toward lower (colder) values at higher latitudes. This latitude variation is much larger than the small variations of OLR with beta angle. Figure 2.7 indicates that median and minimum 16-second ERBS OLR values also have little variation with beta angle. Maximum OLR values in Figure 2.7 are somewhat larger ($\approx 330 \text{ W/m}^2$) near $\beta = 0$ than for large beta angles (e.g., $|\beta| \geq 40^\circ$, where $\text{OLR} \approx 310 \text{ W/m}^2$). This effect is probably a sampling anomaly due to ERBS overflying subsolar (warm) parts of Earth under these conditions. However, this peak in maximum OLR near $\beta = 0$, is not a phenomenon that appears in 99 percentile OLR, which varies no more than about $\pm 5 \text{ W/m}^2$ over all beta angles.

These results lead to the following conclusions regarding sensitivity of albedo and OLR to orbital inclination (latitude) and beta angle:

- Both TOA albedo (at solar zenith angle 0) and OLR depend significantly on range of latitudes encountered at various orbital inclinations. STEM must therefore account explicitly for orbital inclination effects on hot and cold extreme environments.
- There is no need to consider effects of beta angle on statistics of hot and cold extreme environments. Exceptions to this are beta angle effects on orbital-average albedo correction term (Table 2.1), effects on fraction of time spent in Earth's shadow (Equation 1.10), and, perhaps, a short "pulse" of high OLR values near sub-solar points when $\beta \approx 0$ (which can be evaluated by simulation of effects of an OLR pulse by methods described in Sections 3 and 4).

2.3.5 Seasonal and Time-of-Day Variation Figure 2.8 shows a contour plot of mean albedo (at solar zenith angle 0) versus satellite-Sun longitude difference (local solar time). With explicit effects of solar zenith angle removed, this figure shows mean albedo is much more sensitive to latitude than time of day. Figure 2.9 illustrates the same for OLR, except there is a small zone of slightly higher OLR ($\approx 260 \text{ W/m}^2$) near solar noon near absolute latitude 20° . However, this zone of near-noon, high OLR is no more than a few W/m^2 higher than other times of day (see also discussion of Figure 2.7 in Section 2.3.4). Conclusion is time-of-day effects need not be considered explicitly in characterizing hot and cold extreme environments in STEM.

Figure 2.10 shows seasonal variation of monthly-average OLR and shortwave reflected radiation (determined from monthly average albedo) from ERBE data. As expected from Section 1.2.2, reflected shortwave (SW) is largest in January (perihelion) and smallest in July (aphelion). This effect causes a variation in monthly mean SW of about $\pm 8 \text{ W/m}^2$ (i.e., ± 3.5 percent of the $\approx 239 \text{ W/m}^2$ annual mean value (Section

1.2.2)). Monthly OLR values in Figure 2.10 are at a minimum during November-January and at a maximum in July (i.e., approximately out of phase with SW variations but in phase with Northern Hemisphere summer/winter cycle). This effect results from the large amount of land area in the Northern Hemisphere and the fact that land surfaces warm more effectively in Northern Hemisphere summer than do Southern Hemisphere ocean surfaces during its summer. Note when averaged over the year, OLR and SW are in very good global balance (Section 2.2.1).

Because time-of-year effects are relatively small and for reasons discussed in Section 1.2.3, we conclude STEM need not account for monthly or seasonal effects on hot or cold extreme environments. Although this conclusion is reasonable for mission planning purposes, there are valid reasons from a mission operations standpoint to account sometimes for seasonal or monthly variations in various thermal environment components. For example, GOES-9 has encountered a heat-related system component failure (Lawson, 1996) that is compensated for operationally by changing satellite orientation during specific months when highest thermal environmental loads are encountered.

2.4 Hot and Cold Environmental Extremes

2.4.1 Rationale for Defining Extreme Environments Section 2.3 leads us to conclude that statistics to represent hot and cold extreme conditions in STEM must account explicitly for effects of averaging time and orbital inclination (and inclination effect on latitude range). Figures 2.11 and 2.12 show effects of averaging time on maximum, median (50 percentile), and minimum values of albedo (at solar zenith angle zero) and OLR. As expected, averaging time has essentially no effect on median value (or on average value). Small observed effects on median or average values are due to sampling statistics (e.g., due to data gaps, some 16-second observations do not contribute to average values over longer time periods). Effect of averaging time on maximum and minimum albedo and OLR is to decrease maximum-minimum range as averaging time increases (i.e., increased average time decreases variance of albedo and OLR about their median or average value).

Effect of averaging time on both albedo and OLR is illustrated by comparing contour plots in Figure 2.13 (1800-second average) with Figure 2.2 (128-second average). Figure 2.13 represents data density contours (within “boxes” of width 1 W/m² in OLR and height 0.01 in albedo) for 1800-second averages. A total of 13517 data points are represented, with peak data density (50 points per box) occurring at OLR = 226 W/m² and albedo = 0.26. In addition to showing reduced range of maximum-minimum values for albedo and OLR, Figure 2.13 also shows that the (negative) correlation (contour patterns sloping downward to the right in Figure 2.2) is less for larger averaging time.

Quantitative effects of both orbital inclination (latitude) and averaging time on average (arithmetic mean) and standard deviation in albedo and OLR are illustrated in Table 2.2. This table gives values for average and standard deviation of albedo (at solar zenith angle zero) and OLR for averaging times between 16 seconds and 24 hours, and

for orbital inclinations in ranges low (0 to 30 degrees), medium (30 to 60 degrees), or high (60 to 110 degrees). For daytime data (solar zenith angles less than 65 degrees) albedo-OLR cross correlation value is also presented. "All Data" columns show only OLR statistics, since albedo is identically zero for nighttime conditions. Data from all three ERBE satellites is included for evaluating the short averaging times, 30 minutes and shorter. However, for longer averaging times for high inclination orbits the ERBS (60 degree inclination) satellite data was excluded because it would bias the data toward the warm side; it never samples the cold polar environment which high inclination satellites sample every orbit. This produces a shift in the high inclination average OLR values between the ≤ 30 and ≥ 90 minute data. Some bias is probably introduced by including the ERBS data in the short-time averages, but a greater bias (especially in the hot extremes) would result by excluding it because the two remaining satellites were sun synchronous and thus sampled limited local solar times.

Table 2.2 Average and standard deviation in albedo (at solar zenith angle zero) and OLR for low, medium, and high inclination for seven averaging times

<u>Inclination</u>	<u>Avg. Time</u>	<u>Daytime Data</u>					<u>All Data</u>	
		<u>ALB Avg.</u>	<u>ALB S.D.</u>	<u>OLR Avg.</u>	<u>OLR S.D.</u>	<u>Corr.</u>	<u>OLR Avg.</u>	<u>OLR S.D.</u>
low	16 sec	0.18	0.06	246	27	-0.555	245	27
med.	16 sec	0.22	0.08	235	28	-0.674	228	34
high	16 sec	0.23	0.09	233	28	-0.699	221	40
low	128 sec	0.18	0.06	246	26	-0.543	245	26
med.	128 sec	0.22	0.08	235	27	-0.667	229	29
high	128 sec	0.23	0.08	233	28	-0.695	222	34
low	896 sec	0.18	0.05	246	21	-0.413	245	20
med.	896 sec	0.22	0.05	234	18	-0.560	227	22
high	896 sec	0.22	0.04	235	17	-0.547	223	25
low	30 min	0.18	0.04	246	17	-0.317	245	16
med.	30 min	0.22	0.03	234	14	-0.374	227	16
high	30 min	0.22	0.03	235	14	-0.384	223	19
low	90 min	0.18	0.03	246	13	-0.045	245	12
med.	90 min	0.22	0.02	234	12	-0.178	227	11
high	90 min	0.21	0.02	227	8	-0.357	211	5
low	6 hour	0.18	0.01	246	9	0.447	245	9
med.	6 hour	0.22	0.02	234	10	-0.029	227	10
high	6 hour	0.21	0.01	227	4	-0.325	211	3
low	24 hour	0.18	0.01	246	8	0.683	245	8
med.	24 hour	0.22	0.02	234	10	0.032	227	10
high	24 hour	0.21	0.01	227	3	-0.245	211	2

This table shows that (within sampling issues and fluctuations discussed above) average values do not vary with averaging time, but depend significantly on orbital inclination. Standard deviations decrease significantly as averaging time increases, but do not depend very strongly on orbital inclination. In general there are only minor differences in OLR statistics between daytime and all-data categories. An exception to this occurs at short averaging times and high inclination, in which case cold, high-latitude-winter (nighttime) temperatures noticeably reduce short-term average OLR values for all-data (including night) compared with daytime-data. Albedo-OLR correlation values also become smaller in magnitude as averaging time increases.

One conceptual problem with defining hot and cold extreme conditions (especially at short averaging times when albedo-OLR correlation is large and negative) is high albedo is associated with low OLR (and vice versa). We have chosen to address this issue by defining three basic types of hot and cold extremes: albedo extreme, OLR extreme, and combined extreme. Each of these is defined and discussed in following sections.

To illustrate the need for definitions of more than one hot and cold extreme, consider data contour plots in Figure 2.2. Selecting as hot case the combination of maximum albedo with maximum OLR, defines an albedo-OLR combination far outside (to upper right of) the observed data region. Similarly, an extreme cold point defined by the combination of minimum albedo and minimum OLR falls far to the lower left of the observed data region. Adopted definitions for albedo extreme, OLR extreme, and combined extreme, are defined in following sections and patterned after the methodology of Pavelitz (1995). In addition to analyzing combinations such as high albedo with mean OLR, mean albedo with high OLR, etc., Pavelitz also defined three extremal points on albedo-OLR data contours (his points A, B, and C) by subjective examination of data contour plots. The following are well-defined definitions of hot and cold extremes suitable for a computer algorithm.

2.4.2 Albedo Extreme Environments At a given orbital inclination and averaging time, albedo extreme hot environment is defined as the “maximum” albedo value combined with expected (average) value of all OLR data paired with the albedo points exceeding an appropriately-large percentile. Albedo hot extreme for 128-second averaging time is illustrated in Figure 2.14 by the upper set of crossed lines. In this case the hot extreme albedo is 0.47 and associated average OLR is 180 W/m^2 (average of all data points paired with albedos exceeding 0.47). Similarly, albedo cold extreme is defined as “minimum” albedo value combined with expected (average) value of all associated OLR data less than an appropriately-small percentile. Albedo cold extreme for 128-second averaging time is shown as the lower set of crossed lines in Figure 2.14, at albedo = 0.06 and $\text{OLR} = 273 \text{ W/m}^2$. Tabular values for albedo extremes (hot and cold, shown as “Extreme Type = Alb”) are given in Table 2.3, for low, medium, and high inclinations and averaging times from 16 seconds to 24 hours.

Table 2.3 Albedo (at solar zenith angle zero) and OLR (W/m^2) values for mission-critical hot and cold extreme environments at low (0 to 30 degrees), medium (30 to 60 degrees), or high (60 to 110 degrees) inclinations, and averaging times from 16 seconds to 24 hours. Albedo type extremes are labeled "Alb" (OLR type extremes and combined type extremes are defined in Sections 2.4.3 and 2.4.4)

Extreme Type	Avg. Time	Mission-Critical Cold Case						Mission-Critical Hot Case					
		0-30°		30-60°		60-110°		0-30°		30-60°		60-110°	
		Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR
Alb	16 sec	0.06	273	0.06	273	0.06	273	0.43	182	0.48	180	0.50	180
Alb	128 sec	0.06	273	0.06	273	0.06	273	0.42	181	0.47	180	0.49	184
Alb	896 sec	0.07	265	0.08	262	0.09	264	0.37	219	0.36	192	0.35	202
Alb	30 min	0.08	261	0.12	246	0.13	246	0.33	219	0.34	205	0.33	204
Alb	90 min	0.11	258	0.16	239	0.16	231	0.28	237	0.31	204	0.28	214
Alb	6 hr	0.14	245	0.18	238	0.18	231	0.23	248	0.31	212	0.27	218
Alb	24 hr	0.16	240	0.19	233	0.18	231	0.22	251	0.28	224	0.24	224
Comb	16 sec	0.13	225	0.15	213	0.16	212	0.30	298	0.31	267	0.32	263
Comb	128 sec	0.13	226	0.15	213	0.16	212	0.29	295	0.30	265	0.31	262
Comb	896 sec	0.14	227	0.17	217	0.17	218	0.28	291	0.28	258	0.28	259
Comb	30 min	0.14	228	0.18	217	0.18	218	0.26	284	0.28	261	0.27	260
Comb	90 min	0.14	228	0.19	218	0.19	218	0.24	275	0.26	257	0.26	244
Comb	6 hr	0.16	232	0.19	221	0.20	224	0.21	264	0.24	248	0.24	233
Comb	24 hr	0.16	235	0.20	223	0.20	224	0.20	260	0.24	247	0.23	232
OLR	16 sec	0.40	150	0.40	151	0.40	108	0.22	331	0.21	332	0.22	332
OLR	128 sec	0.38	154	0.38	155	0.38	111	0.22	326	0.22	331	0.22	331
OLR	896 sec	0.33	173	0.34	163	0.33	148	0.22	318	0.22	297	0.20	294
OLR	30 min	0.30	188	0.27	176	0.31	175	0.17	297	0.21	282	0.20	284
OLR	90 min	0.25	206	0.30	200	0.26	193	0.20	285	0.22	274	0.22	250
OLR	6 hr	0.19	224	0.31	207	0.27	202	0.19	269	0.21	249	0.22	221
OLR	24 hr	0.18	230	0.25	210	0.24	205	0.19	262	0.21	245	0.20	217

Table 2.4 Albedo (at solar zenith angle zero) and OLR (W/m^2) values for non-critical hot and cold extreme environments at low (0 to 30 degrees), medium (30 to 60 degrees), or high (60 to 110 degrees) inclinations, and averaging times from 16 seconds to 24 hours. Albedo type extremes are labeled “Alb” (OLR type extremes and combined type extremes are defined in Sections 2.4.3 and 2.4.4)

Ext-reme Type	Avg. Time	Non-critical Cold Case						Non-critical Hot Case					
		0-30°		30-60°		60-110°		0-30°		30-60°		60-110°	
		Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR
Alb	16 sec	0.09	270	0.10	267	0.10	267	0.29	205	0.36	201	0.38	197
Alb	128 sec	0.09	267	0.10	265	0.10	265	0.29	211	0.35	202	0.37	199
Alb	896 sec	0.10	261	0.13	252	0.14	252	0.26	225	0.29	213	0.28	213
Alb	30 min	0.12	257	0.16	242	0.17	244	0.24	234	0.27	223	0.26	223
Alb	90 min	0.13	249	0.18	238	0.18	230	0.22	246	0.26	229	0.24	219
Alb	6 hr	0.15	241	0.19	233	0.19	230	0.20	252	0.25	231	0.23	224
Alb	24 hr	0.16	240	0.19	235	0.19	230	0.20	252	0.25	232	0.23	224
Comb	16 sec	0.15	236	0.19	227	0.20	225	0.21	260	0.23	240	0.24	237
Comb	128 sec	0.16	237	0.19	227	0.20	225	0.21	260	0.23	240	0.24	238
Comb	896 sec	0.16	237	0.20	226	0.20	227	0.21	261	0.23	241	0.23	240
Comb	30 min	0.16	237	0.20	225	0.20	226	0.21	258	0.23	240	0.23	242
Comb	90 min	0.16	237	0.20	225	0.21	224	0.20	258	0.23	241	0.23	232
Comb	6 hr	0.17	237	0.20	226	0.21	226	0.19	255	0.23	242	0.22	230
Comb	24 hr	0.17	236	0.20	226	0.20	225	0.19	257	0.23	241	0.23	230
OLR	16 sec	0.30	195	0.33	183	0.35	164	0.17	285	0.17	280	0.17	280
OLR	128 sec	0.29	198	0.33	184	0.34	164	0.17	284	0.17	279	0.17	279
OLR	896 sec	0.26	209	0.28	189	0.27	172	0.18	279	0.18	264	0.18	263
OLR	30 min	0.23	216	0.25	200	0.25	190	0.18	274	0.20	258	0.20	258
OLR	90 min	0.20	225	0.23	209	0.24	202	0.19	268	0.21	254	0.21	242
OLR	6 hr	0.18	231	0.23	212	0.23	205	0.19	261	0.21	242	0.21	216
OLR	24 hr	0.17	233	0.23	212	0.23	207	0.18	258	0.21	241	0.21	215

2.4.3 OLR Extreme Environments At a given orbital inclination and averaging time, OLR extreme hot environment is defined as “maximum” OLR value combined with expected (average) value of all albedo data in the pairs that exceed this OLR percentile. OLR hot extreme for 128-second averaging time is illustrated in Figure 2.15 by the right set of crossed lines. In this case, OLR hot extreme OLR is $331 W/m^2$ and average albedo is 0.22 for all data points with OLR exceeding $331 W/m^2$. Similarly, OLR cold extreme is defined as “minimum” OLR value combined with expected (average) value of all albedo data paired with the OLR points less than this percentile. OLR cold extreme for 128-second averaging time is shown as the left set of crossed lines in Figure 2.15, at $OLR = 155 W/m^2$ and $albedo = 0.38$. From this figure we see that (because of effects of strong negative correlation at this averaging time) OLR cold extreme is near albedo hot extreme, while OLR hot extreme is somewhat near albedo cold extreme. Tabular values for OLR extremes (hot and cold, shown as “Extreme Type = OLR”) are

given in Table 2.3, for low, medium, and high inclinations and averaging times from 16 seconds to 24 hours.

2.4.4 Combined Extreme Environments At a given orbital inclination and averaging time, combined extreme hot environment is defined as the point in albedo-OLR space at which 0.04 percent of data are up (higher albedo) and to the right (larger OLR) of the extreme point, illustrated by the upper-right set of crossed lines in Figure 2.16. The second condition determining the location of combined hot extreme is a point where normalized variates for albedo and OLR are equal (normalized variate is deviation from average value divided by standard deviation of the distribution). Normalized variates are evaluated using averages and standard deviations given in Table 2.2. Similarly, combined extreme cold environment is defined as the point in albedo-OLR space having equal normalized variates for albedo and OLR and at which 0.04 percent of data are down (lower albedo) and to the left (smaller OLR) of the extreme point, illustrated by the lower-left set of crossed lines in Figure 2.16. The large dot roughly mid-way between combined hot and combined cold points is the average albedo average OLR point. Tabular values for combined extremes (hot and cold shown as “Extreme Type = Comb”) are given in Table 2.3, for low, medium, and high inclinations and averaging times from 16 to 5400-seconds.

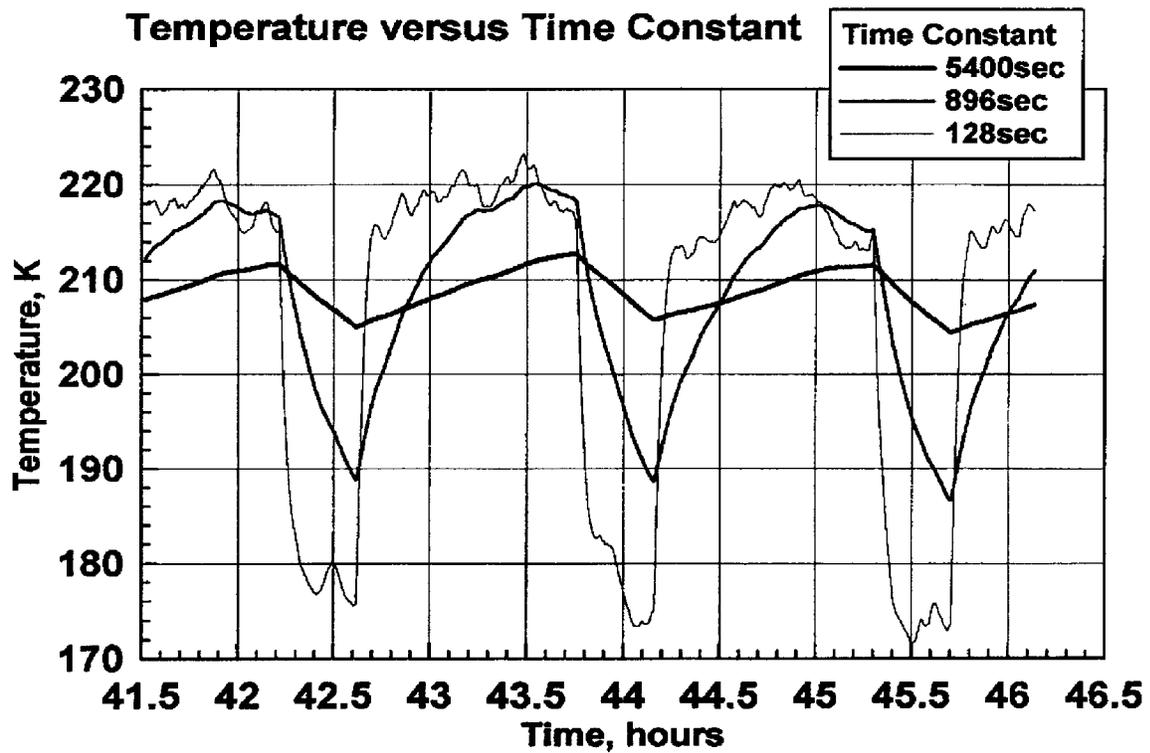


Figure 2.1 Temperature for a spherical satellite with various thermal time constants, derived from numerical solution of Equation 2.1.

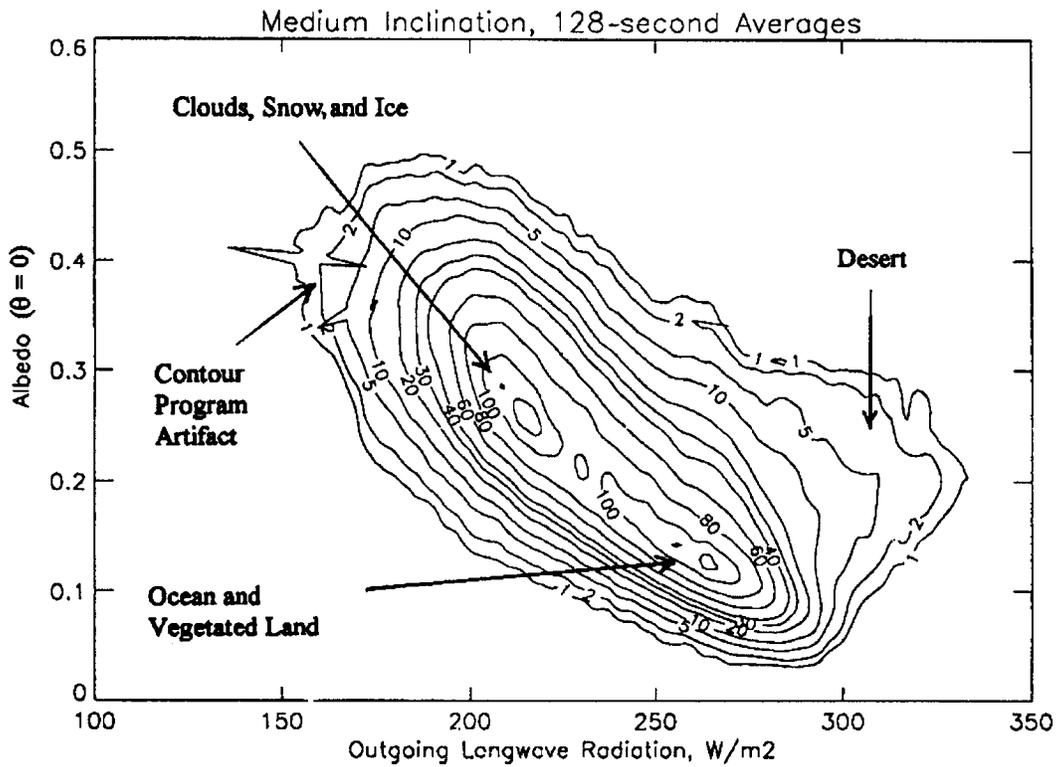


Figure 2.2 Contours of ERBS-observed frequency of top-of-atmosphere (TOA) albedo (at solar zenith angle 0) and outgoing longwave radiation (OLR): 128 second averaging time, medium inclination orbit. Frequency contours are also number density, i.e., number of observations during the observation period that occurred within albedo-OLR “boxes” of “width” 1 W/m² in OLR and “height” 0.01 in albedo. The total number of observations is 132,841.

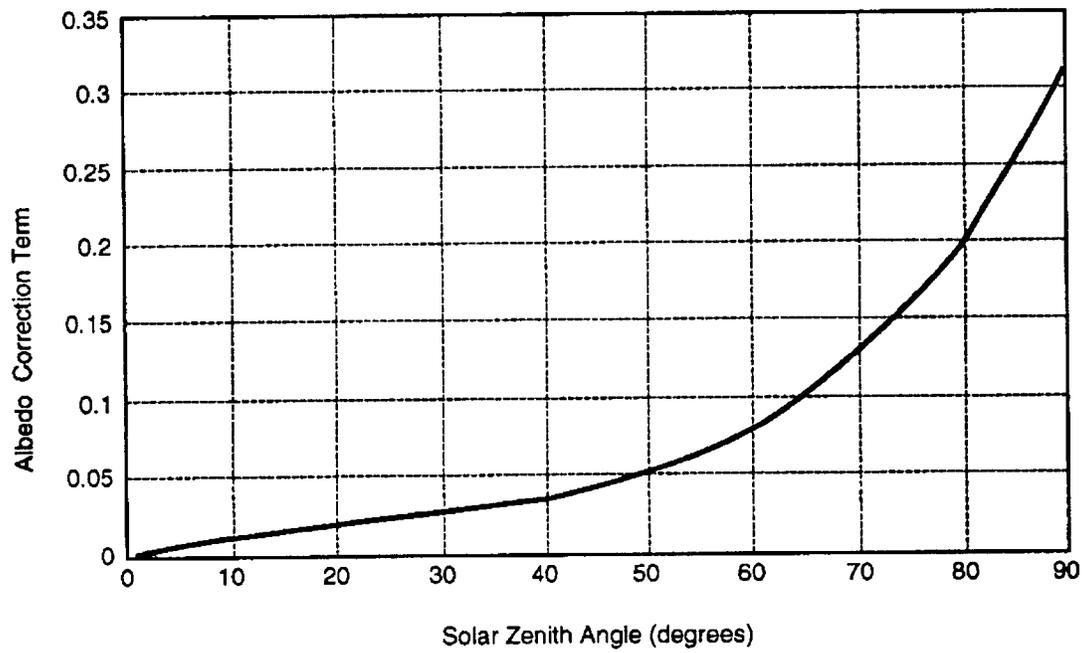


Figure 2.3 Albedo correction term, $c(\theta)$, as a function of solar zenith angle, θ .

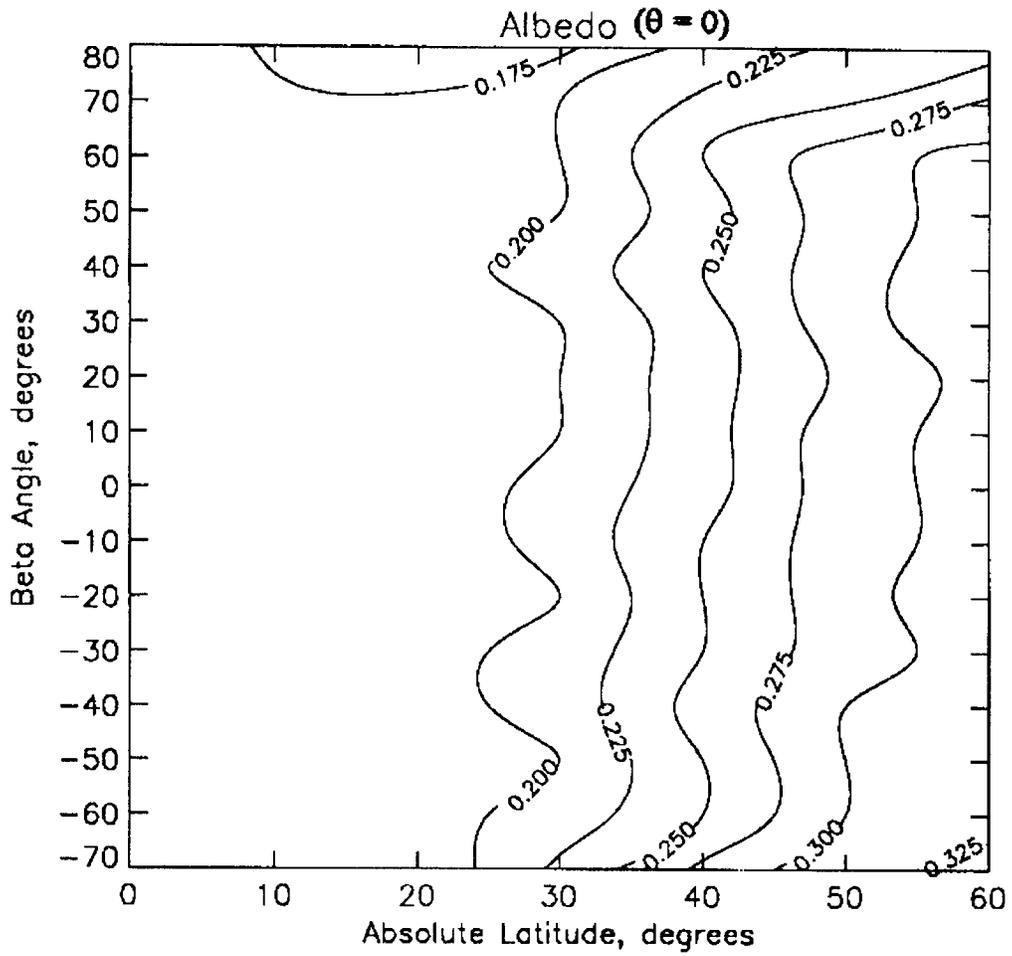


Figure 2.4 Average TOA albedo (at solar zenith angle 0) versus orbital beta angle and latitude.

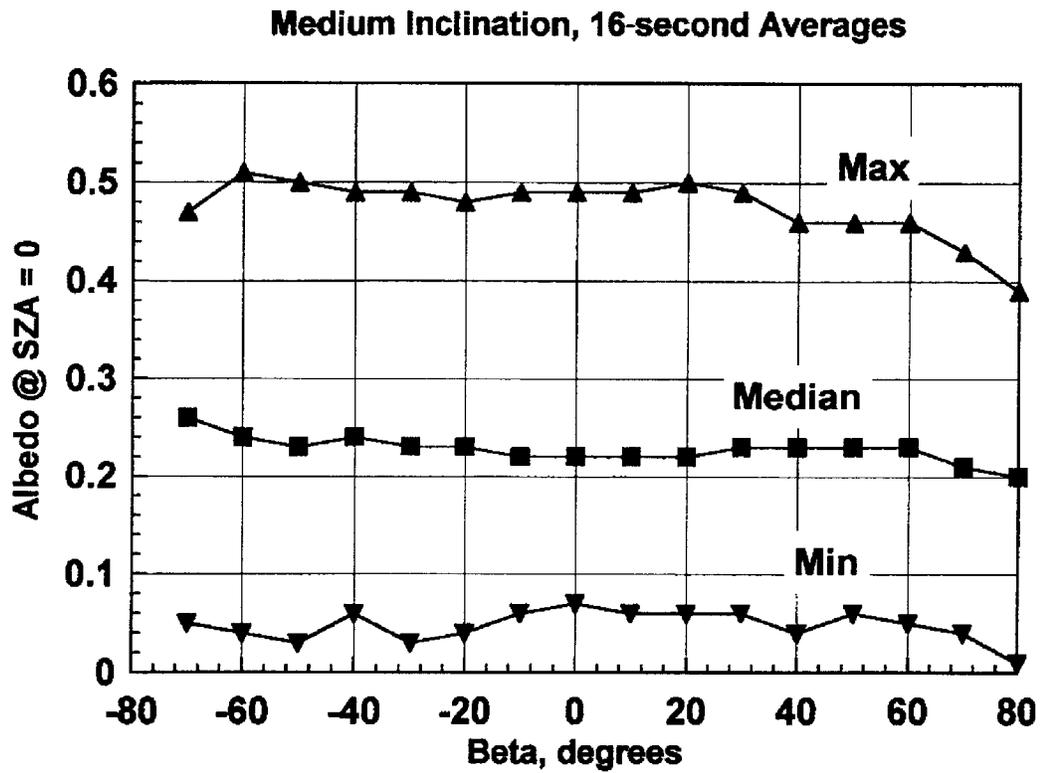


Figure 2.5 Maximum, median, and minimum TOA albedo (at solar zenith angle 0) as a function of orbital beta angle.

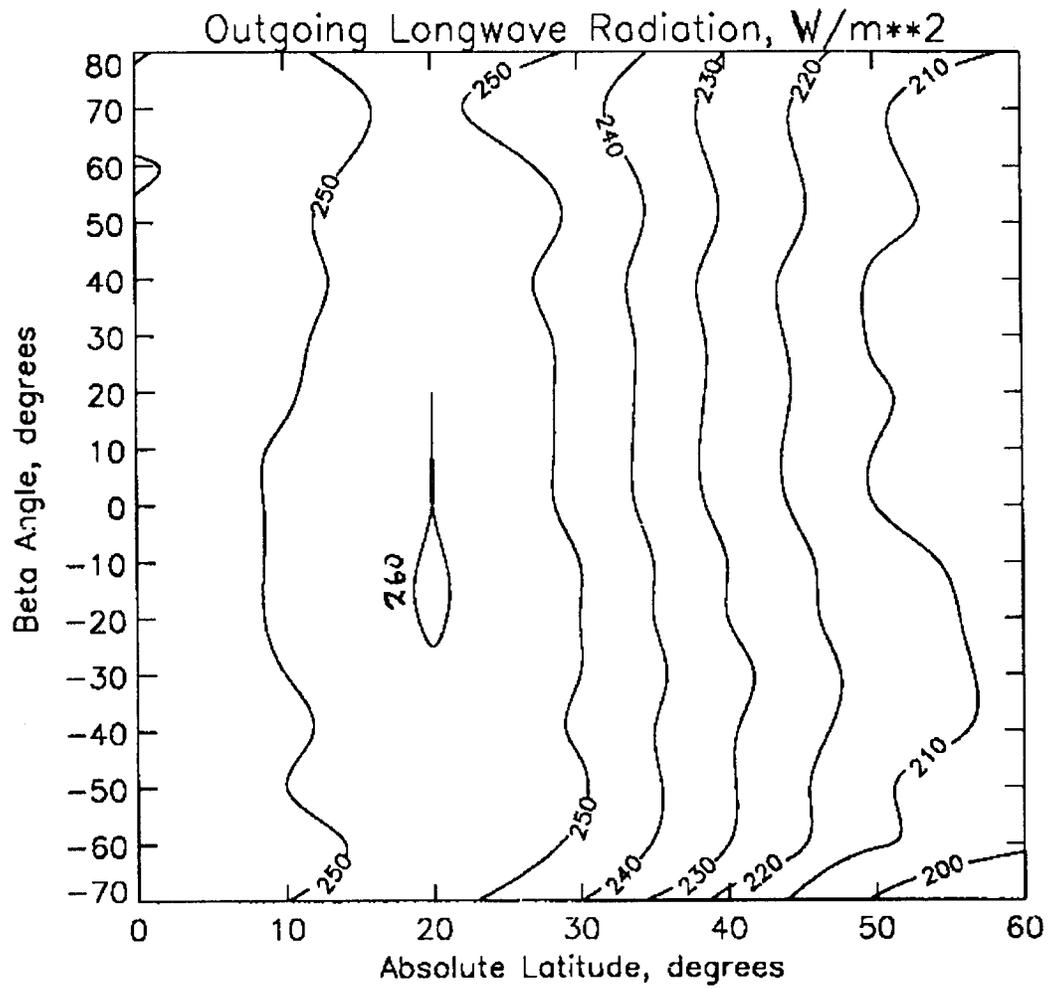


Figure 2.6 Average OLR versus orbital beta angle and latitude.

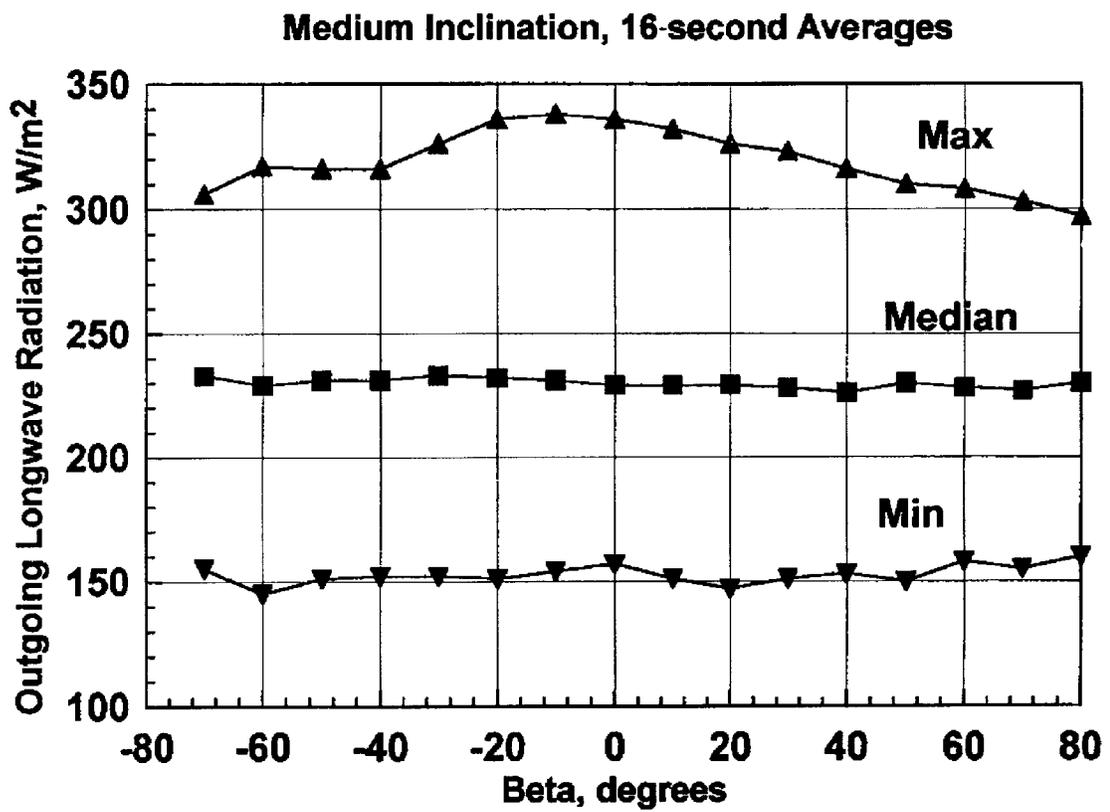


Figure 2.7 Maximum, median, and minimum OLR as a function of orbital beta angle.

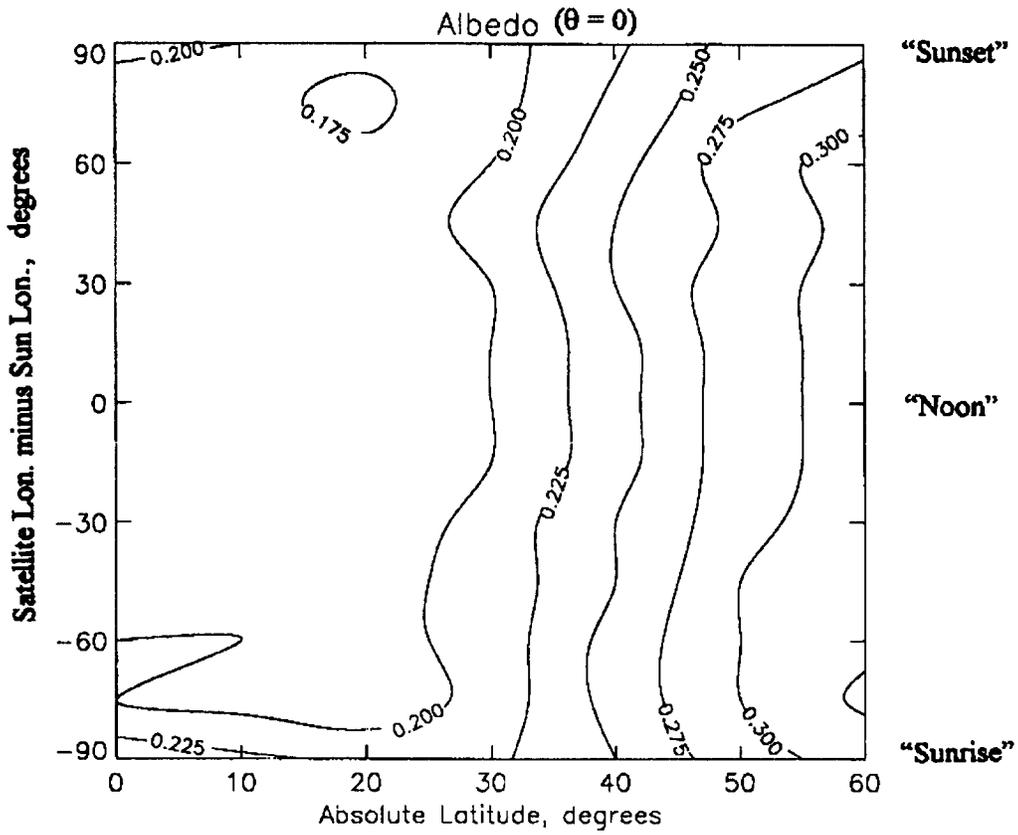


Figure 2.8 Average TOA albedo (at solar zenith angle 0) versus satellite-Sun longitude (or local solar time) and latitude.

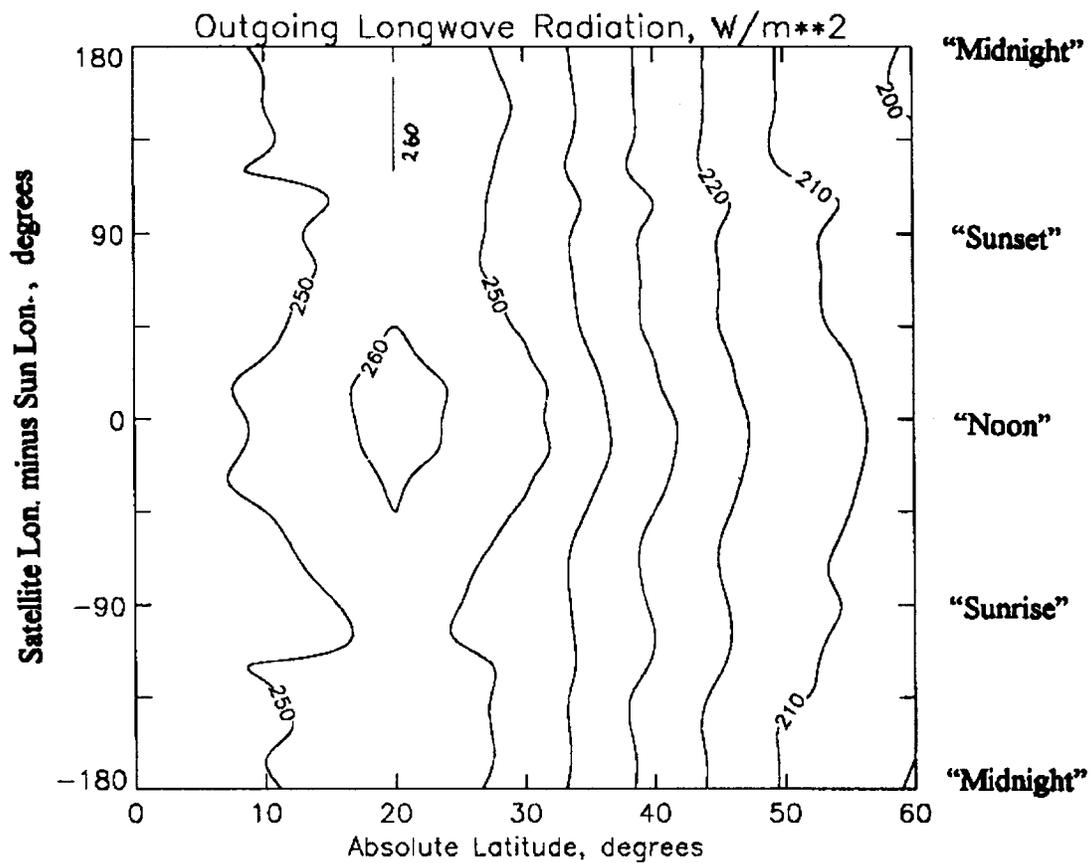


Figure 2.9 Average OLR versus satellite-Sun longitude (or local solar time) and latitude.

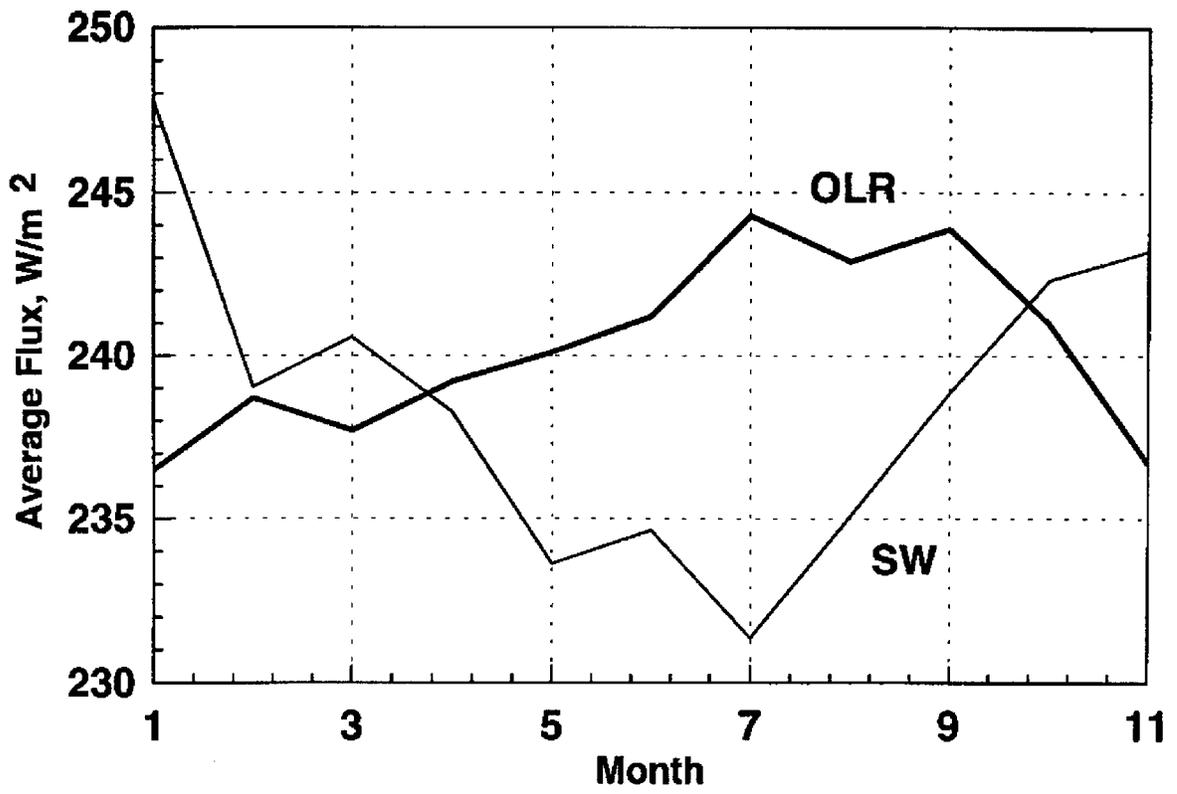


Figure 2.10 Global monthly average OLR and shortwave reflected radiation versus month.

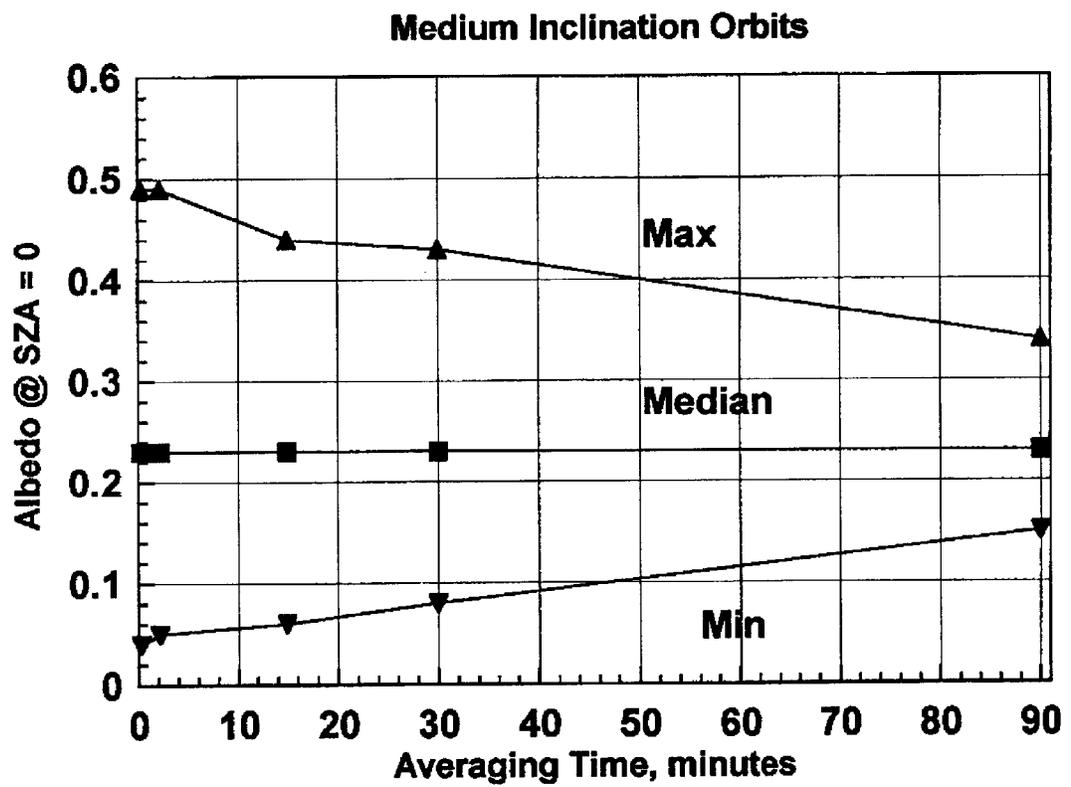


Figure 2.11 Maximum, median, and minimum TOA albedo (at solar zenith angle 0) as a function of averaging time.

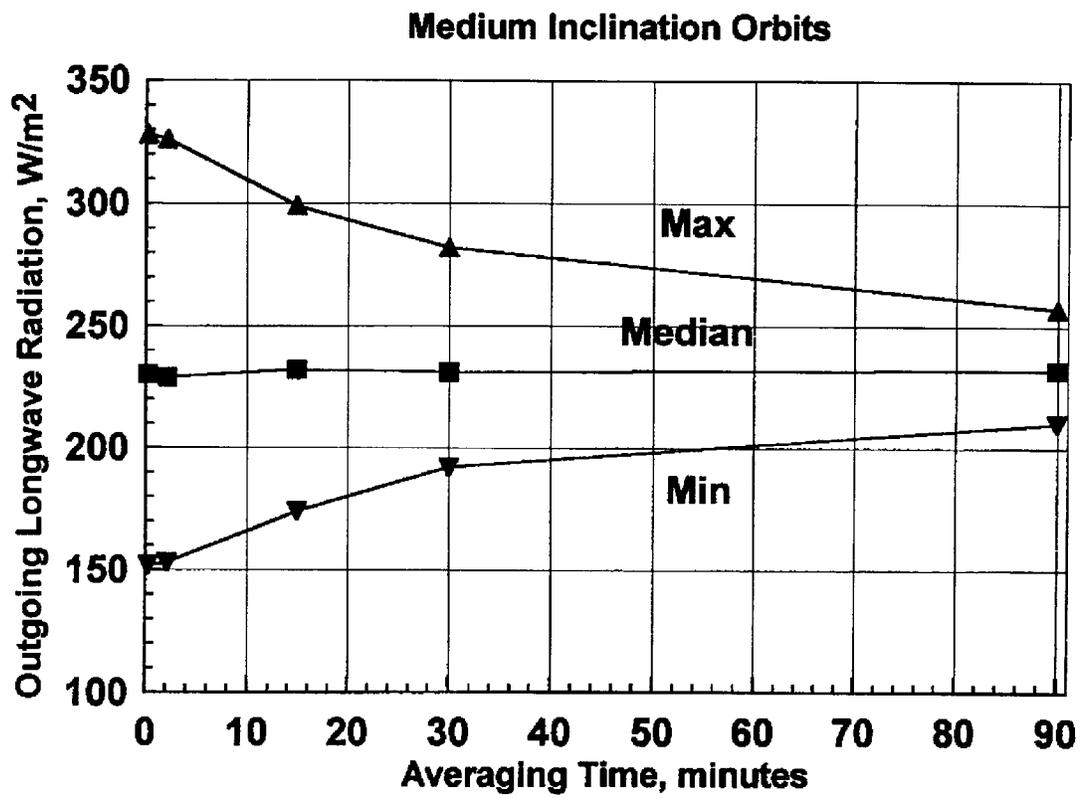


Figure 2.12 Maximum, median, and minimum OLR as a function of averaging time.

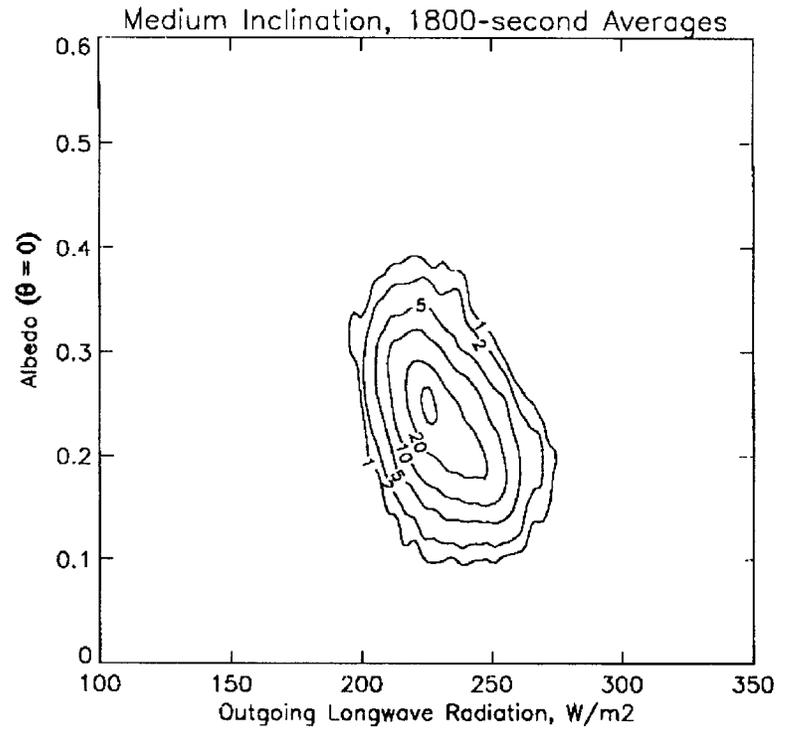


Figure 2.13 Contours of ERBS-observed frequency of top-of-atmosphere (TOA) albedo (at solar zenith angle 0) and outgoing longwave radiation (OLR): 1800- second averaging time, medium inclination orbit.

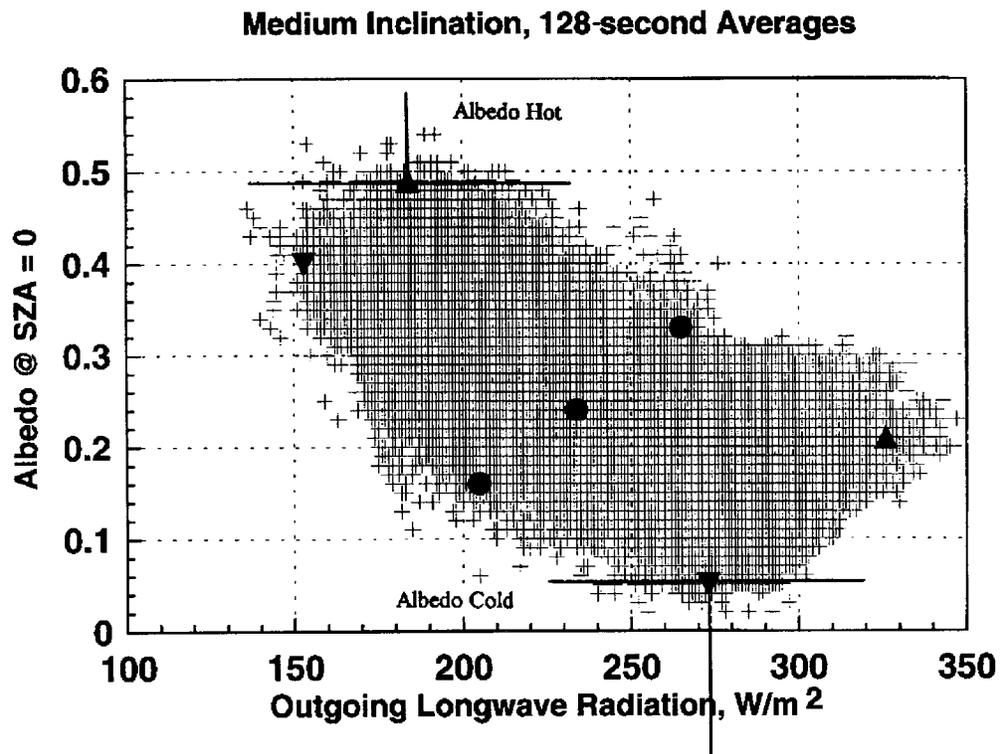


Figure 2.14 Distribution of TOA albedo (at solar zenith angle 0) and OLR for medium inclination, 128-second averages, illustrating albedo extreme type hot and cold values.

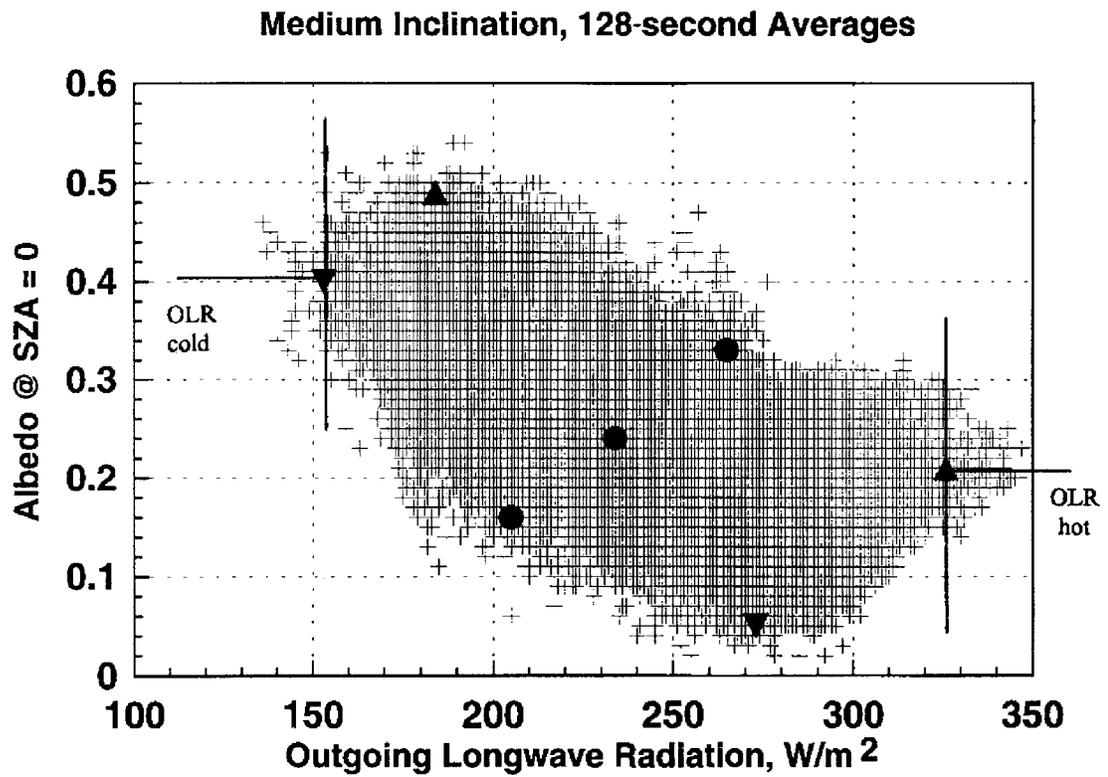


Figure 2.15 Distribution of TOA albedo (at solar zenith angle 0) and OLR for medium inclination, 128-second averages, illustrating OLR extreme type hot and cold values.

Medium Inclination, 128-second Averages

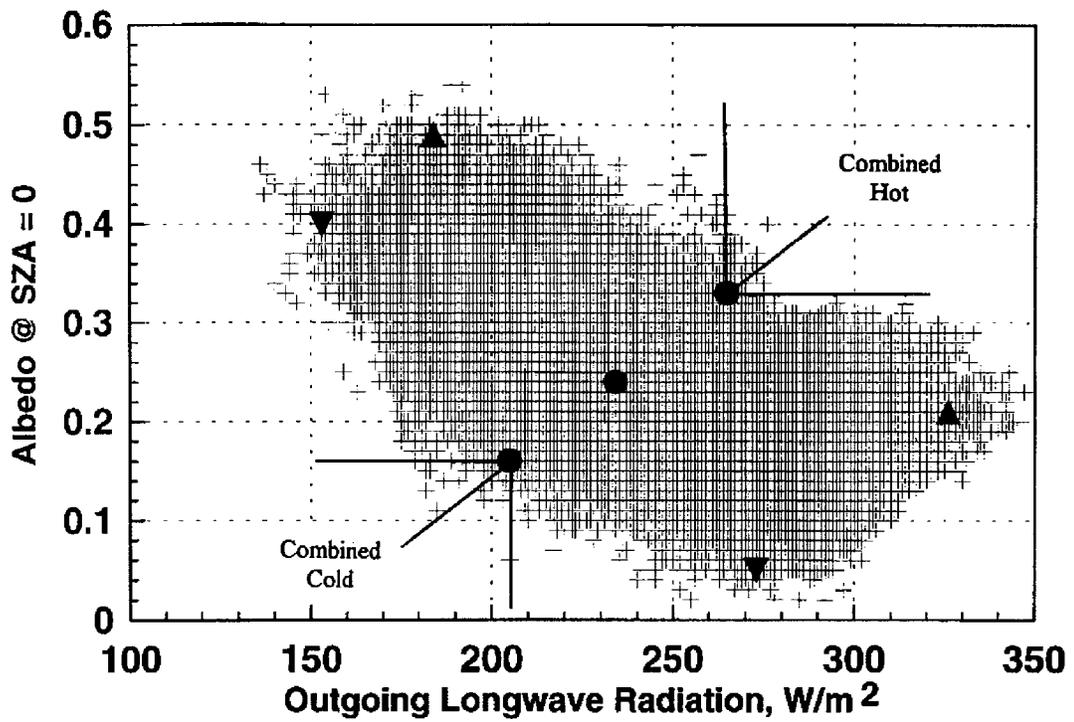


Figure 2.16 Distribution of TOA albedo (at solar zenith angle 0) and OLR for medium inclination, 128-second averages, illustrating combined extreme type hot and cold values.

3. Simple Thermal Environment Model (STEM) Program

3.1 Methodology

3.1.1 Function of the STEM Program The function of STEM is to assist a thermal analyst in selecting design point values for thermal environment parameters for spacecraft in Earth orbit. Thermal environment parameters output by the STEM program consist of one or more values of albedo and OLR from Table 2.3 for mission-critical systems, or from Table 2.4 for non-critical systems. These, together with a value of direct solar irradiance defined in Section 1.2.3, specify the environmental part of system heat load. Steps that STEM goes through in suggesting output values of albedo and OLR include: (1) estimation of thermal time constant and selection of averaging time consistent with thermal time constant(s) of the system, (2) selection of appropriate extreme type (albedo, combined or OLR extreme), based on thermal properties of the system and estimated environmental heat loads, and (3) selection of albedo and OLR values for combinations of heat load pulses of various durations. STEM also performs various corrections or computations as part of the selection process. These include correction of environmental heat loads for orbital altitude, computation of fraction of orbit in Earth's shadow, corrections of average albedo for solar zenith angle (and beta angle), and selection of low/medium/high orbital inclination range based on input value of orbital inclination angle.

3.1.2 Computation of Thermal Time Constant From values of program input (Section 3.2), STEM computes mean (orbital average) temperature, T_0 , and thermal time constant, τ . T_0 is computed from Equation 2.4,

$$T_0 = [q_0 / (\epsilon \sigma)]^{1/4} \quad (3.1)$$

where q_0 is heat load per unit area (Q_0 / A), ϵ is longwave emittance of the system, and σ is Stefan-Boltzmann constant ($5.670 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). Orbital average heat load (per unit area) is computed via

$$q_0 = q_s + q_{sw} + q_{LW} + q_{int} \quad (3.2)$$

where q_s is orbital average direct solar heat load, q_{sw} and q_{LW} , respectively are shortwave (Earth-reflected) and longwave (Earth-emitted) environmental heat load components, and

q_{int} is internal heat load per unit area. The environmental heat load components are computed via

$$q_{\text{S}} = \frac{1}{4} (1 - f_{\text{s}}) \alpha S \quad (3.3)$$

$$q_{\text{SW}} = \frac{1}{4} (1 - f_{\text{s}}) \alpha S \langle a(\theta) \rangle (r_{30} / r)^2 \langle \cos(\theta) \rangle \quad (3.4)$$

$$q_{\text{LW}} = \frac{1}{4} (r_{30} / r)^2 \epsilon E_{\text{e}} \quad (3.5)$$

where $\frac{1}{4}$ is the form factor for a spherical satellite (Equation 2.14), f_{s} is the fraction of orbit in Earth's shadow (Equation 1.10), α is shortwave absorptance, S is direct solar irradiance (Section 1.2.3), $\langle a(\theta) \rangle$ is solar-zenith-angle-averaged albedo (Table 2.1), $(r_{30} / r)^2$ corrects radiation fluxes to satellite orbital radius (r) from radius at top-of-atmosphere ($r_{30} = r_{\text{e}} + 30$ km), $\langle \cos(\theta) \rangle$ is orbital average cosine solar zenith angle ($\cos(\beta) / 2$ where β is orbital beta angle), and E_{e} is outgoing longwave (Earth-emitted) radiation (OLR). Orbital average OLR and albedo values for Equations 3.4 and 3.5 are taken from 5400-second (90-minute) average values (for appropriate orbital inclination) from Table 2.2.

Since heat loads differ for hot and cold extremes, separate hot and cold mean temperatures are computed and are used (Equation 2.7) to compute separate hot and cold values for thermal time constant, τ . These values of time constant are used in STEM selections of averaging time (Sections 3.2 and 3.3). Note, since time constant depends on total heat load (Equation 2.7), internal heat load can affect time constant.

3.1.3 Selection of Thermal Extreme Type STEM selects thermal extreme type (albedo, combined or OLR extreme) based on a comparison of environmental heat load (per unit area), q_{ENV} , for the three cases. Environmental heat load is that portion of total heat load from Earth environment (reflected and emitted) components alone. Thus

$$q_{\text{ENV}} = q_{\text{SW}} + q_{\text{LW}} \quad (3.6)$$

where q_{SW} and q_{LW} are evaluated in Equations 3.4 and 3.5, except that separate values (for each of the three extreme types) are computed, using albedo and OLR values (for appropriate orbital inclination, averaging time, and extreme type) in Table 2.3 (mission-critical components) or Table 2.4 (non-critical components).

For cold extreme type, STEM suggests the type that yields smallest of the three cold values of q_{ENV} . For hot extreme type, STEM suggests the type that yields largest of the three hot values of q_{ENV} . As an option STEM-suggested extreme type can be overridden and extreme type selected by the user (Section 3.2).

3.2 How to Run STEM

To run STEM first acquire the FORTRAN source code, described in the appendix and the required TABLEMC.DAT and TABLENC.DAT input data files. Compile the code into an executable program (called STEM). The executable program and input data file are assumed to be in the same file directory. Create next a NAMELIST format input file, STEMIN (Table 3.1). On UNIX or Windows 95 systems file names STEM, STEMIN, and TABLEMM.DAT may be in lower case.

Table 3.1 Sample STEM input file, STEMIN in NAMELIST format

```
$stemin
missioncrit = 1
units = 1
mass = 1.
Cp = 1000.
area = 1.
Qint = 0.
Scold = 1317.
Shot = 1419.
alpha = 0.422
epsilon = 0.765
altitude = 604.
beta = 6.
inclination = 57.
coldcase = 0
hotcase = 0
$End
missioncrit = 1 for mission critical cases (reads tablemc.dat) or
                0 for non-critical cases (reads tablenc.dat)
units           = 1 for MKS units, 2 for British units
mass           = satellite component mass [kg or lb]
Cp             = specific heat capacity [J/(kg*K) or Btu/(lb*R)]
area           = component exposed area [m**2 or ft**2]
Qint           = internal heat load (W or Btu/hr)
Shot           = design hot solar irradiance [W/m**2 or Btu/(hr*ft**2)]
Scold          = design cold solar irradiance [W/m**2 or Btu/(hr*ft**2)]
alpha          = component absorptance [unitless]
epsilon        = component emittance [unitless]
altitude       = orbital altitude [km or nautical miles]
beta           = minimum angle between orbital plane and Sun [deg.]
inclination    = orbital inclination [degrees]
coldcase       = cold extreme case; 0 = let program pick
hotcase        = hot extreme case; 0 = let program pick
```

If parameter “units” = 1, STEM interprets input variables in International System (SI or MKS) units; if units = 2, STEM interprets input parameters in British units (see comments in Table 3.1). Values for mass, specific heat capacity, and area apply to

system component for which evaluation of thermal time constant is desired. Gilmore (1994) gives a list of component alpha and epsilon values in his appendix A. He also provides a list of specific heat values in his appendix C.

For systems with many components, the analyst may wish to do STEM runs for a range of values, e.g., one for largest (most massive or longest time constant) component and one for smallest (least massive or shortest time constant) component. STEM output from multiple runs may be combined and used as input values of albedo and OLR for a long-period average (background) case (consistent with longest time constant) with a superimposed “pulse” or pulses of albedo and OLR with time duration(s) consistent with shorter time constant system components (Sections 3.3 and 4).

Normally, STEM selects hot and cold extreme types (albedo, combined, or OLR extreme) and provides albedo and OLR values accordingly. If the analyst wishes to override STEM choices for either hot or cold extreme case, select a non-zero value for either “coldcase” or “hotcase” in the STEMIN file. For this option, 1 denotes albedo extreme, 2 combined extreme, and 3 OLR extreme.

Table 3.1 gives default values for all STEM input variables. Only those variables with values different from defaults need be input by the STEMIN file (e.g., for all default conditions the STEMIN file may be an empty NAMELIST format file, i.e.,

```
$STEMIN  
$END
```

After the STEMIN file is created, run STEM with screen output by entering the executable program name, e.g.

```
STEM
```

or, if output is too long to fit the screen at one time, pipe output to “more”, for scrolling purposes by entering

```
STEM | more.
```

To route output to a file (e.g. “filename”), enter

```
STEM > filename .
```

3.3 Interpretation of STEM Output

3.3.1 Preliminary STEM Output Table 3.2 shows STEM output for default input data given in Table 3.1. Most output in the first five lines is echoed back from input values. Units (MKS or British) are shown to indicate selected type. These five lines include orbital average albedo correction $\langle c(\theta) \rangle$ (Table 2.1), albedo correction

evaluated at minimum solar zenith angle $\theta = |\beta|$, and fraction of orbit in sunlight $(1 - f_s)$ from Equation 1.10).

3.3.2 Heat Loads, Time Constant and Extreme Type The main output of STEM is two sets of values for cold extreme and hot extreme cases. Quantities are direct solar irradiance (Section 1.2.3), direct solar heat load (per unit area Equation 3.3), orbital average heat load (per unit area Equation 3.2, 3.4, and 3.5), orbital average (equilibrium) temperature (from Equation 3.1), thermal time constant (Equation 2.7), and averaging period (based on time constant) for selecting albedo and OLR values (Tables 2.2 and 2.3), and environmental heat loads (per unit area, Equation 3.6) for albedo extreme, combined extreme, and OLR extreme cases. STEM's automatic selection of extreme type is based on lowest cold environmental heat load and highest hot environmental heat load. In Table 3.2 STEM selected OLR extreme for both cold and hot cases.

3.3.3 Albedo and OLR Output Following selection of extreme type, STEM outputs albedo and OLR values (Table 3.2), for various averaging times. Three averaging times are identified as base values ("Base@ 5400 sec", "Base@Time Const", and "Base@Mult. Pulse"). As illustrated in Figures 3.1, in the following section, and in Section 4, base values are usable as single representative values at appropriate averaging times. Four averaging times (1800, 896, 128, and 16 seconds) are identified as candidate for simulation of pulse values. Depending on details of system time constants (illustrated in Figures 3.2 and 3.3, and discussed more fully in the following section and Section 4), the analyst may choose to add one or more pulses of OLR (and albedo) on top of the appropriate base values.

Base Values Figure 3.1 illustrates a time series of observed ERBE OLR data, with various base values, from Table 3.2, superimposed. Hot and cold base values "at Time Constant" in Figure 3.1 are those which capture the extremes of OLR appropriate for the system time constant (≈ 400 -seconds in this case), for the full time series, not just for the segment illustrated. Base values "at Time Constant" are the highest (hottest) and lowest (coldest) of the base values. Hot and cold base values "at 5400 sec" (90 minutes) in Figure 3.1 are those appropriate for system components having long thermal time constants. For components having time constants longer than 5400 seconds, STEM outputs "Base@21600 sec" (6 hours) or "Base@86400 sec" (24 hours), as appropriate. "Base@ 5400 sec" values do not capture the extremes of variation that result from short duration hot and cold excursions of OLR. They do, however, represent appropriate OLR values as "filtered" by the slow thermal response of system components having long thermal time constants.

Base Values for Single Pulses As discussed in the following section and Section 4, base values at 5400 sec (or longer, if appropriate) are suitable as "background" values on which to superimpose (single) pulses of various duration (to capture the variability of combined long-time-constant and short-time-constant system components). Table 3.2 gives OLR type extreme cold base values of OLR. If STEM selects either albedo type

extreme or combined type extreme then OLR base value for OLR extreme is also provided for cold case.

Table 3.2 Example STEM output for default input data given in Table 3.1

Simple Thermal Environment Model (STEM)

Mission Critical Case
 Mass = 1.0000 kg Cp = 1000.0000 J/(kg*K) Area = 1.0000 m**2
 alpha = .422 epsilon = .765 alpha/epsilon = .552
 beta = 6.0 deg. Avg, Min.za Albedo correction applied = .04 .01
 Inclination = 57.0 degrees. (Medium) Altitude = 604. km
 Fraction of orbit in direct sun = .634

	Cold	Hot	
	-----	-----	
Direct Solar Irrad =	1317.0	1419.0	W/m**2
Direct Heat Load =	88.1	94.9	W/m**2
Internal Heat Load =	.0	.0	W/m**2
Avg Total Heat Load =	135.4	143.0	W/m**2
Equilibrium Temp. =	236.4	239.6	Kelvin
Time Constant =	436.	419.	seconds
	7.3	7.0	minutes
	.121	.116	hours
Averaging Period =	128	128	seconds
	2.1	2.1	minutes
Environ. Heat Load =	47.7	49.3	Albedo Extreme
W/m**2	41.3	56.2	Combined Extreme
	40.5	63.7	OLR Extreme
Use Extreme Type =	OLR	OLR	
Base@ 5400 sec =	.34	.26	Albedo (base value)
W/m**2	200.	274.	OLR (base value)
Pulse@ 1800 sec =	.28	.22	Albedo (Min. za)
W/m**2	176.	282.	OLR (Min. za)
W/m**2	176.	282.	OLR (Max. za)
Pulse@ 896 sec =	.35	.23	Albedo (Min. za)
W/m**2	163.	297.	OLR (Min. za)
W/m**2	163.	297.	OLR (Max. za)
Base@Time Const =	.42	.26	Albedo (base value)
W/m**2	155.	331.	OLR (base value)
Pulse@ 128 sec =	.39 (*)	.23 (*)	Albedo (Min. za)
W/m**2	155. (*)	331. (*)	OLR (Min. za)
W/m**2	155. (*)	331. (*)	OLR (Max. za)
Pulse@ 16 sec =	.41 (*)	.22 (*)	Albedo (Min. za)
W/m**2	151. (*)	332. (*)	OLR (Min. za)
W/m**2	151. (*)	332. (*)	OLR (Max. za)
Base@Mult.Pulse =	.26	.26	Albedo (average value)
W/m**2	234.	234.	OLR (average value)

(*) - This pulse is shorter than the relevant time constant.

Base Values for Multiple Pulses The base value "at Multiple Pulse" in Figure 3.1 is the average value of OLR (for the full time series, not just the segment illustrated).

This base value is suitable as “background” value on which to superimpose (either hot or cold) multiple pulses of various duration (see following discussion on multiple pulses). In addition to base OLR values, STEM output (Table 3.2) also gives comparable base albedo values. STEM automatically corrects all base albedo values (from uncorrected values in Table 2.3) by the amount $\langle c(\theta) \rangle$, the correction value, $c(\theta)$, averaged over all solar zenith angles. The correction amount applied to the base values by STEM is given as “Avg Albedo correction applied” in Table 3.2.

Single Pulse Values Figure 3.2 shows the same time series of ERBE OLR data as in Figure 3.1, with hot and cold 896 sec pulse values superimposed on the hot and cold “Base@5400 sec” background values. The time series of values including pulses are generated with the TESTSTEM program, as described in Section 4. For the sample output (Table 3.2; \approx 400-seconds time constant), appropriate pulse durations would be either 896-seconds or 1800-seconds. STEM output also includes pulse values from averaging times shorter than the time constant: 128 and 16 seconds in this example. Asterisks on STEM output for these values remind the user they are for pulse lengths shorter than the thermal time constant. As shown in Figure 3.2, hot and cold pulses are simulated twice per orbit, one centered on the minimum solar zenith angle point and one centered on the maximum solar zenith angle point. With the maximum solar zenith angle point (most nearly anti-solar point) being in the Earth’s shadow (where albedo has no effect), OLR type extreme cold value pulse should always be used at maximum solar zenith angle. STEM output also includes albedo pulse values. STEM automatically corrects all albedo pulse values by an amount $c(\beta)$, the correction value at minimum solar zenith angle (i.e. beta angle). The correction amount applied to the pulse values by STEM is given as “Min.za Albedo correction applied” in Table 3.2.

Multiple Pulse Values Optionally, two or three pulse values from STEM output may be superimposed simultaneously on a background (base value). For such a case, the appropriate background is the average (“Base@Mult. Pulse”) value, used for both hot and cold pulses. Figure 3.3 illustrates this case with three OLR pulses (1800, 896, and 128 sec). As with the single pulse case, OLR type extreme OLR should always be used at maximum solar zenith angle.

The following section gives more complete descriptions of STEM outputs and their application for various cases. Section 4 discusses how to run and interpret output from the TESTSTEM program. To aid in selection of OLR and albedo values to use in a full thermal analysis, TESTSTEM lets the analyst test various STEM output choices for a simple-geometry satellite system.

3.3.4 Sample Cases Using STEM Output Depending on the satellite system under consideration, not all albedo-OLR output from STEM is required. To illustrate some typical situations, using example output (Table 3.2) consider the following cases:

1. Single (Short) Time Constant If the satellite is small and light and a short time constant applies for the entire system, the albedo and OLR values for “Base@Time Const” are used as single, fixed values for hot extreme and cold extreme simulations (see “Base@Time Const” values in Figure 3.1).

2. Single (Long) Time Constant If the satellite is relatively large and heavy and a long time constant applies for the entire system, the albedo and OLR values for “Base@ 5400 sec” (or longer, if applicable) can be used as single, fixed values for hot extreme and cold extreme simulations. If the time constant is between 5400 sec (90 minutes) and 21600 sec (6 hours), values for “Base@Time Const” are the same as “Base@ 5400 sec”.

3. Multiple (Long and Short) Time Constants If the satellite consists of multiple components including both long and short time constants, then “Base@ 5400 sec” (or longer, if applicable) albedo and OLR values are used as “background” values (to capture appropriately the temperature behavior of long time constant components). To capture quicker thermal response of short time constant components, a single pulse of albedo and OLR is superimposed on this background (see Figure 3.2). The most appropriate single pulse is one with averaging time just longer than the short time constant. Use background albedo or OLR of “Base@ 5400 sec” values, with a pulse of albedo and OLR given by 896 second values (for example case with 400-seconds shortest time constant). See Section 4 for information on simulation of pulse cases via TESTSTEM.

4. Multiple Time Constants, Multiple Albedo/OLR Pulses If the satellite is as in Case 2, but multiple pulses of albedo and OLR are desired, use “Base@Mult.Pulse” values (average over the full data set) as background. Then albedo and OLR pulses of any durations can be superimposed (see Figure 3.3). Most appropriate in the example case (shortest time constant \approx 400-seconds) are pulses of 1800, 896 and 128-seconds (i.e., longer and just shorter than the shortest time constant satellite component). See Section 4 for information on simulation of single and multiple pulse cases via TESTSTEM.

3.3.5 Sensitivity to Absorptance and Emittance An illustration of STEM application is the sensitivity study to shortwave absorptance, α , and longwave emittance, ϵ , given in Table 3.3. This table contrasts equilibrium temperature, time constant, environmental heat loads, and selection of extreme type (evaluated in Table 3.2) with STEM analyses for two other pairs of α and ϵ values. The case in Table 3.2 is α and ϵ characteristic of flame-sprayed aluminum oxide (Wolfe and Zeiss, 1989). Additional cases in Table 3.3 are anodized aluminum and polished-degreased aluminum. Except for variation in α and ϵ , all other parameters are the same as in Table 3.2. Table 3.3 shows the following: (1) equilibrium temperature increases as ratio α/ϵ increases, (2) although it varies significantly with α and ϵ values, time constant is not a monotonically increasing function of α/ϵ , and (3) the type of extreme (albedo, combined, or OLR extreme) depends on α/ϵ , with albedo extreme more likely for high α/ϵ values and OLR extreme more likely for low α/ϵ values.

Table 3.3 Sensitivity of equilibrium temperature, T_0 , thermal time constant, τ , and environmental heat load, q_{ENV} , to shortwave absorptance, α , and longwave emittance, ϵ . Superscripts C and H denote extreme types (albedo, combined, or OLR extreme) selected by STEM. T_0 and τ values are average hot and cold cases, with \pm indicating range between cold and hot cases. Absorptance and emittance values are from Table 2-31 of Wolfe and Zeiss (1989).

Parameter	Anodized Aluminum	Aluminum Oxide	Aluminum, Polished & Degreased
SW Absorptance (α)	0.150	0.422	0.387
LW Emittance (ϵ)	0.770	0.765	0.027
α / ϵ Ratio	0.19	0.55	14.33
Equil. Temp. (T_0), K	203 \pm 1	238 \pm 2	498 \pm 5
Time Constant (τ), sec	686 \pm 10	427 \pm 9	1320 \pm 37
q_{ENV} (W/m ²) Alb. Cold	45.6	47.7	5.6 ^C
Comb. Cold	37.0	41.3	8.3
OLR Cold	30.6 ^C	40.5 ^C	13.8
q_{ENV} (W/m ²) Alb. Hot	36.4	49.3	15.7 ^H
Comb. Hot	47.8	56.2	13.1
OLR Hot	57.3 ^H	63.7 ^H	11.2

C - Cold Extreme Type Selected

H - Hot Extreme Type Selected

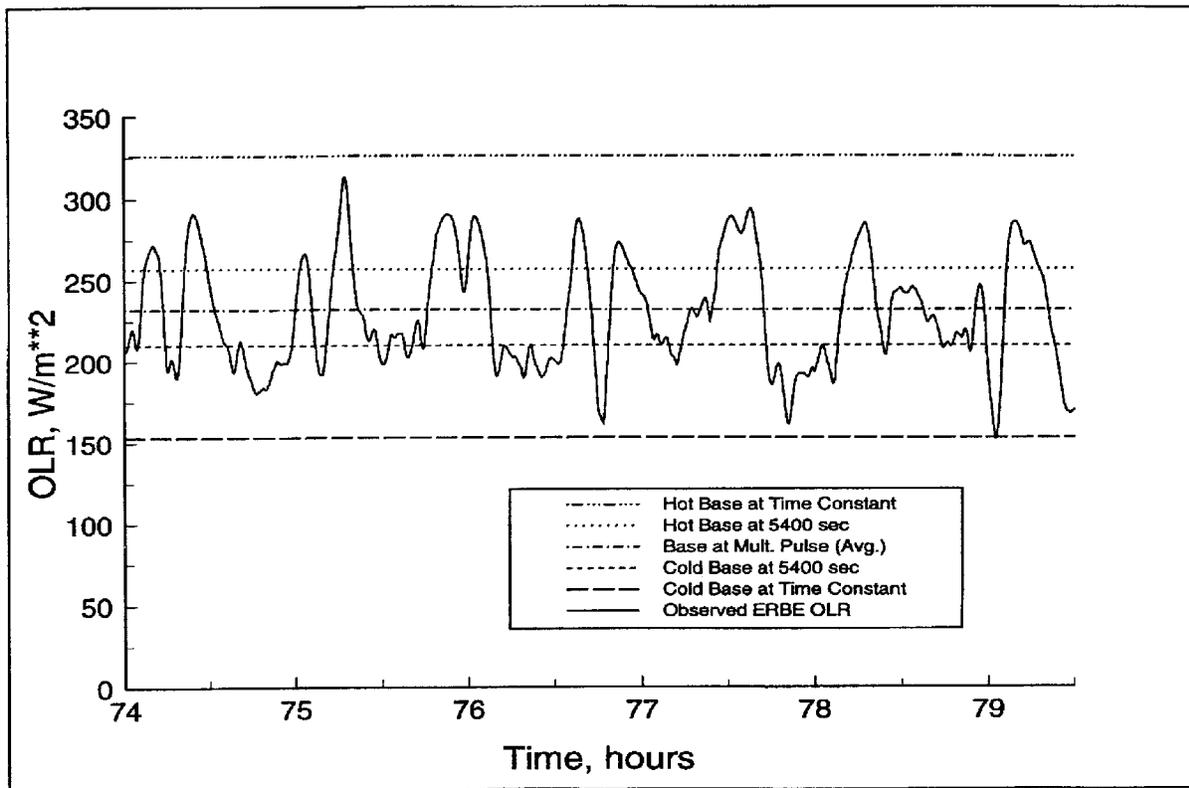


Figure 3.1 Sample time series of observed ERBE OLR data with hot and cold base values superimposed

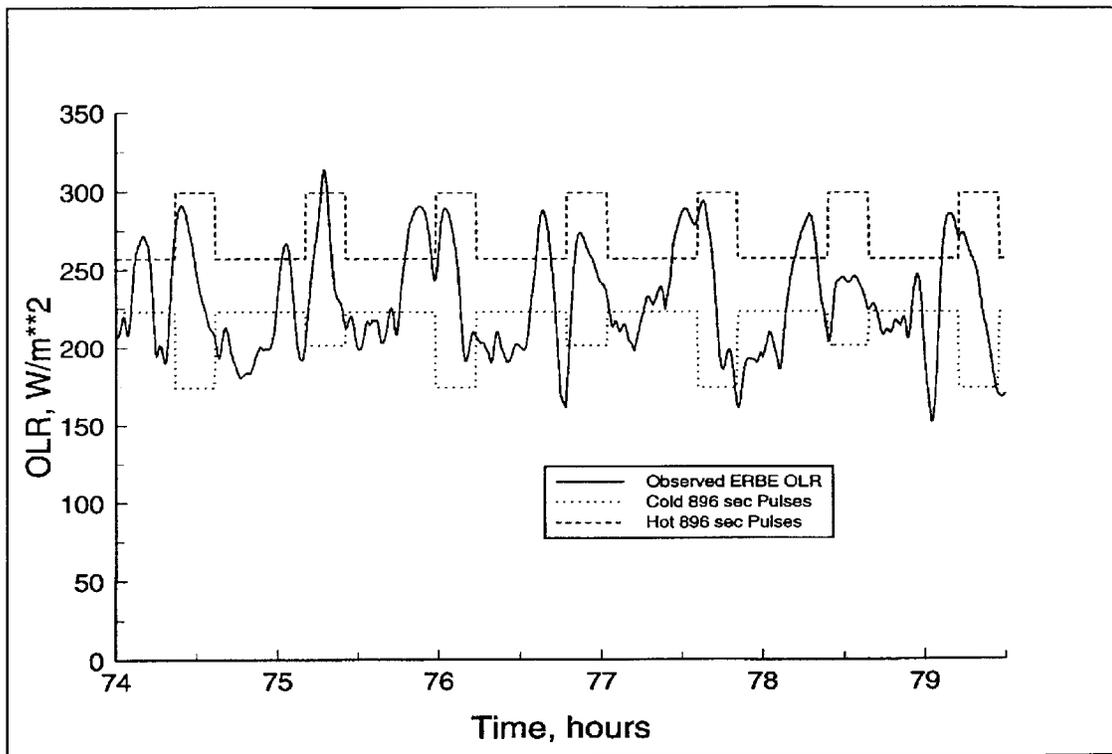


Figure 3.2 Sample time series of observed ERBE OLR data with hot and cold pulses (896 sec) superimposed on hot and cold base values (at time constant).

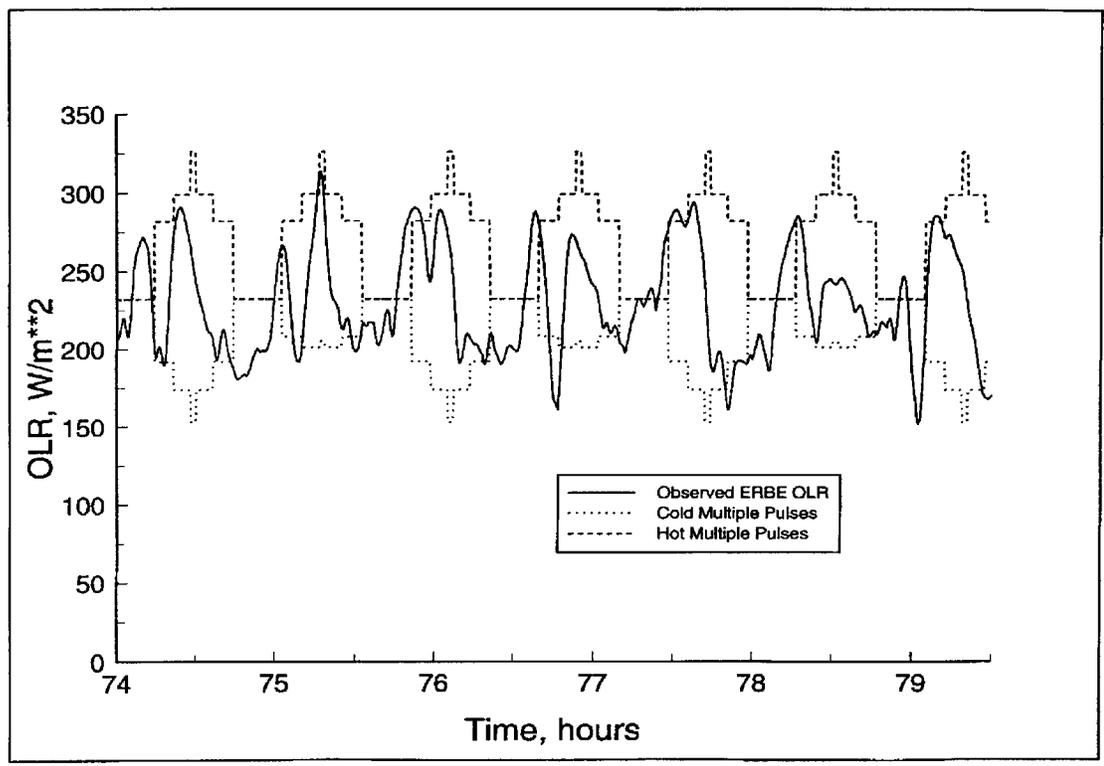


Figure 3.3 Sample time series of observed ERBE OLR data with multiple hot and cold pulses superimposed on base (at multiple pulse).

4. Simple Time Series Test Program (TESTSTEM)

4.1 Methodology

4.1.1 Function of the TESTSTEM Program The two primary purposes for TESTSTEM are to allow thermal analysts to test various output values from STEM as an aid in their selection process (e.g. choice of extreme type) and to compare time series thermal response of a simplified satellite system exposed to real variations in albedo and OLR (ERBE observations) with thermal response of systems exposed to albedo/OLR pulses of various durations and amplitudes (STEM output).

4.1.2 Computation of Time Series Thermal Response TESTSTEM computes time series temperature variation for a given set of input values by solving the simplified radiative heat transfer equation (Equation 2.1),

$$(M C_p / A) dT / dt = q - \epsilon \sigma T^4 \quad (4.1)$$

where q is heat load per unit area (i.e. Q/A), computed as in Equations 3.2 to 3.5, except with local values solar zenith angle, θ , albedo at solar zenith angle, $a(\theta)$, and OLR, E_e , rather than orbital average values; similarly, a local sunlight indicator ($F_s = 1$ or 0) is used in place of orbital average sunlight fraction f_s . Solutions to Equation 4.1 are obtained by Newton's forward difference scheme over a time step of 16-seconds (ERBE data sampling interval).

The two solution modes for TESTSTEM are (1) albedo, $a(\theta)$, and OLR = E_e , (along with date and time, solar zenith angle, beta angle and orbital altitude) are from observed time series of a user-selected ERBE data set, and (2) time variations of albedo and OLR are simulated by model values from STEM output, possibly including up to three pulses of albedo and OLR values. In TESTSTEM pulses are always centered on the point in the orbit at minimum solar zenith angle (most nearly sub-solar point) and on the maximum solar zenith angle location (most nearly anti-solar point). Two separate runs of TESTSTEM are required: one for hot case and one for cold case. Pulses are applied at both minimum zenith angle and maximum zenith angle for both hot case and cold case. In STEM output testing mode TESTSTEM substitutes STEM values for albedo and OLR time variations, but uses the same time series of day and time, solar zenith angle, beta angle, and orbital altitude values from ERBE data. To aid in sensitivity studies TESTSTEM allows simultaneous time series simulations of system components having two different thermal time constants.

4.2 How to Run TESTSTEM

To run TESTSTEM, first, acquire the FORTRAN source code described in the appendix, along with ERBE data input files (named CTSYYMMS.TXT, where YY is year, MM is month, and S is satellite number, i.e., 1 = NOAA9, 2 = ERBS, 3 = NOAA10). Compile the code into an executable program (called TESTSTEM). The executable program and input data file must be in the same file directory. Next, create a NAMELIST format input file, TESTIN, Table 4.1. On UNIX or Windows 95 systems, file names TESTSTEM, TESTIN, and CTSYYMMS.TXT may be in lower case.

If parameter “units” is 1, TESTSTEM interprets input variables in International System (SI or MKS) units and OLR values in W/m^2 . If units = 2, TESTSTEM interprets input parameters in British units and OLR values in $BTU/(hr\ ft^2)$. ERBE OLR time series input values are always interpreted in W/m^2 .

TESTSTEM simulates either a hot case or a cold case, but only one during a given run. Therefore, either hot or cold values of solar irradiance (from Section 1.2.3) should be selected.

Two different system components (designated 1 or 2 and characterized by time constant, τ , SW absorptance, α , and LW emittance, ϵ) are simulated on each run.

Base (background) values of albedo (\bar{a}) and OLR (\bar{L}) must be provided. Optionally, up to three pulses may be superimposed, by specifying OLR values (L_{maxza} and L_{minza}) and albedo value (a_{minza} ; a_{maxza} , is assumed 0), and pulse durations (seconds). Any pulse length input of 0 and pulses for which no NAMELIST input is provided are ignored. Pulses are centered on the minimum solar zenith angle point and maximum solar zenith angle point in the orbit.

Average height, h , and average beta angle, $\bar{a}\beta$, must be provided for initial orbital average heat load calculations. Actual time series variations of solar zenith angle, beta angle, and orbital altitude are taken from the ERBE data input file.

Parameters, $n1st$ and $nlast$, determine starting and ending records of the ERBE data input file to be processed. To allow thermal equilibrium after startup, $n1st$ should be 500 or greater and $nlast$, $n1st + 1000$, or larger. The file used in this example (cts86012.txt) has 11961 records. If input value of $nlast$ is larger than number of records in the file, TESTSTEM reads and processes to end-of-file and terminates normally.

Parameter $iuseERBE = 1$, causes ERBE albedo data to be corrected from solar zenith angle 0 to observed solar zenith angle. Use of $iuseERBE = 0$ assumes that STEM model input values have had solar zenith angle corrections applied, so no further correction is made. If $iuseERBE = 1$, all albedo and OLR values are from the ERBE data input file and it is not necessary to input albedo or OLR values in the TESTIN file (values included are ignored when $iuseERBE = 1$).

After TESTIN is created, TESTSTEM is run with screen output by entering

TESTSTEM

or, if output is too long to fit on the screen at one time, output may be piped to “more”, for scrolling purposes, by entering

Table 4.1 Sample TESTSTEM input file, TESTIN, in NAMELIST format

```
$testin
filename = 'cts86012.txt'
units = 1
S0 = 1419.
tau1 = 5400.
alpha1 = 0.422
epsilon1 = 0.765
tau2 = 128.
alpha2 = 0.422
epsilon2 = 0.765
abar = 0.26
lbar = 234.
aminza(1) = 0.22
lmaxza(1) = 282.
lminza(1) = 282.
pulse(1) = 1800.
aminza(2) = 0.23
lmaxza(2) = 297.
lminza(2) = 297.
pulse(2) = 896.
aminza(3) = 0.23
lmaxza(3) = 331.
lminza(3) = 331.
pulse(3) = 128.
h = 604.
avbeta = 6.
nlst = 500
nlast = 11000
iuseERBE = 0
$End
```

Table 4.2 - Descriptive explanation of TESTSTEM example input

```

filename = ERBE data file name
units    = 1 for MKS units; 2 for British
S0       = Direct solar irradiance [ W/m**2 or BTU/(hr*ft**2) ]
qint     = internal heat load [ W heat per m**2 surface area or
          Btu/hr heat per ft**2 surface area ]
tau1     = time constant number 1 (sec)
alpha1   = shortwave (SW) absorptance #1
epsilon1 = longwave (LW) emittance #1
tau2     = time constant number 2 (sec)
alpha2   = SW absorptance #2
epsilon2 = LW emittance #2
abar     = base (background) albedo value
lbar     = base (background) OLR [ W/m**2 or BTU/(hr*ft**2) ]
aminza(1) = minimum zenith angle (min za) albedo, pulse #1
lminza(1) = min za OLR, pulse #1 [ W/m**2 or BTU/(hr*ft**2) ]
lmaxza(1) = maximum zenith angle (max za) OLR, pulse #1
pulse(1)  = time duration of pulse #1 (sec)
aminza(2) = min za albedo, pulse #2
lminza(2) = min za OLR, pulse #2 [ W/m**2 or BTU/(hr*ft**2) ]
lmaxza(2) = max za OLR, pulse #2 [ W/m**2 or BTU/(hr*ft**2) ]
pulse(2)  = time duration of pulse #2 (sec)
aminza(3) = min za albedo, pulse #3
lminza(3) = min za OLR, pulse #3 [ W/m**2 or BTU/(hr*ft**2) ]
lmaxza(3) = max za OLR, pulse #3 [ W/m**2 or BTU/(hr*ft**2) ]
pulse(3)  = time duration of pulse #3 (sec)
h         = orbital altitude (km or nautical miles)
avbeta   = average beta angle (deg)
nlst     = first file record to process
nlst     = last file record to process
iuseERBE = 1 for observed ERBE data, 0 for STEM model data

```

TESTSTEM | more .

To route output to a file (e.g. "filename"), enter

TESTSTEM > filename .

4.3 Interpretation of TESTSTEM Output

4.3.1 Example TESTSTEM Output Example (screen) output from TESTSTEM, for TESTIN input data of Table 4.1, is shown in Table 4.3. This output indicates the ERBE data file used as source of time, solar zenith angle, beta angle, and orbital altitude values (and source of albedo and OLR values if iuseERBE = 1). The output also indicates whether ERBE data or STEM model values are the source of albedo and OLR

information and which units convention (MKS or British) was used. The remainder of example TESTSTEM output is described in Table 4.4.

Table 4.3 - Example TESTSTEM output for TESTIN input data in Table 4.1

```

file = cts86012.txt      Model Input Alb/OLR
Input/Output units are MKS
[temperatures in kelvin; fluxes in W/m**2]
      n1st,nlast=      500      11000
      S0,qint=      1419.      .0000
      tau1,tau2=      5400.      128.0
      alpha1,alpha2=      .4220      .4220
      epsilon1,epsilon2=      .7650      .7650
      CpMa1,CpMa2=      .1289E+05      305.6
      h,avbeta=      604.0      6.000
      Q01,Q02=      143.0      143.0
      T01,T02=      239.6      239.6
      abar,Lbar=      .2600      234.0
      fsun=      .6342
aminza(1),Lminza(1)=      .2200      282.0
pulse(1),Lmaxza(1)=      1800.      282.0
aminza(2),Lminza(2)=      .2300      297.0
pulse(2),Lmaxza(2)=      896.0      297.0
aminza(3),Lminza(3)=      .2300      331.0
pulse(3),Lmaxza(3)=      128.0      331.0
      avg h,beta=      603.7      6.286
      aavg,astd=      .2491      .1623E-01
      Lavg,Lstd=      270.0      29.94
      xcor,avsun=      -.4569      .6348
      Q1avg,Q2avg=      147.8      147.8
      Q1std,Q2std=      78.38      78.38
      T1avg,T2avg=      241.4      233.7
      T1sig,T2sig=      5.128      36.81
      Time,orbs=      48.89      30.33
      numtot,iuseERBE=      10500      0
      Minimum T1, T2 =      232.2      177.1
      Maximum T1, T2 =      249.2      270.0

```

Table 4.4 - Descriptive explanation of TESTSTEM example output

n1st,nlast=	First and last line of ERBE file processed
S0,fsun=	Direct solar irradiance, and fraction of orbit in direct sun (estimated from input values)
tau1,tau2=	Time constants (sec) for components 1 and 2
alpha1,alpha2=	SW absorptance for components 1 and 2
epsilon1,epsilon2=	LW emittance for components 1 and 2
CpMa1,CpMa2=	Product of heat capacity (C_p) and mass (M), divided by area (A), for components 1 and 2
h,avbeta=	Input values for average orbital altitude, and beta angle over the time period analyzed (n1st to nlast)
Q01,Q02=	Orbital average heat loads (per unit area) for components 1 and 2 (based on h and avbeta)
T01,T02=	Equilibrium temperatures for components 1 and 2 (based on Q01 and Q02)
abar,Lbar=	Base (background) albedo and OLR
aminza(1),Lminza(1)=	Albedo, OLR for pulse 1 at minimum zenith angle
pulse(1),Lmaxza(1)=	Duration (sec) and OLR for pulse 1 at max za
aminza(2),Lminza(2)=	Albedo, OLR for pulse 2 at minimum zenith angle
pulse(2),Lmaxza(2)=	Duration (sec) and OLR for pulse 2 at max za
aminza(3),Lminza(3)=	Albedo, OLR for pulse 3 at minimum zenith angle
pulse(3),Lmaxza(3)=	Duration (sec) and OLR for pulse 3 at max za
avg h,beta=	Observed average orbital altitude and beta angle from the portion of the ERBE data file analyzed
aavg,astd=	Computed average and standard deviation of time series of albedo values
Lavg,Lstd=	Computed average and standard deviation of time series of OLR values
xcor,avsun=	Albedo-OLR cross correlation (may exceed -1 if astd or Lstd is small), and observed fraction of orbit in sunlight
Q1avg,Q2avg=	Time-series average heat load (per unit area) for components 1 and 2
Q1std,Q2std=	Time-series standard deviations in heat load for components 1 and 2
T1avg,T2avg=	Time series average temperature for components 1 and 2
T1sig,T2sig=	Time series standard deviation in temperature for components 1 and 2
Time,orbs=	Duration (hours) and number of orbits analyzed in the time series (n1st to nlast)
numtot,iuseERBE=	Total number of points analyzed, and value of iuseERBE (1 = ERBE data, 0 = STEM input values)
Minimum T1, T2 =	Minimum (coldest) temperature calculated during time series analyzed, for components 1 and 2
Maximum T1, T2 =	Maximum (hottest) temperature calculated during time series analyzed, for components 1 and 2

4.3.2 TESTSTEM Graphics Output In addition to the output shown in Tables 4.3 and 4.4, a file (TESTSTEM.TXT) suitable for input to a graphics program is also produced. This file contains one line per time simulated. Each line contains time (hours), albedo term, OLR, heat load, Q1, for system 1, temperature, T1, (K or R) for system 1, heat load, Q2, for system 2, and temperature, T2, (K or R) for system 2. OLR and heat loads are in W/m^2 for MKS units or $BTU/(hr\ ft^2)$ for British units. The albedo term is albedo at solar zenith angle θ , multiplied by $\cos(\theta)$, and multiplied by 1000 (as a convenient way to put albedos into a range compatible for plotting with OLR values).

As evidenced by sample data in Figure 4.1, ERBE OLR and albedo values undergo significant short-period fluctuations. In this figure, albedo is at solar zenith angle zero, with no adjustment for $\cos(\theta)$, but has been multiplied by 1000 for scaling purposes. Within the sunlit portion of the orbit on the left of Figure 4.1, albedo varies from less than 0.13 to greater than 0.46. Notice the evidence of large negative correlation between albedo and OLR near 0.65 hours and 0.9 hours, when the ERBS satellite apparently passed over warm, dark vegetation or ocean surfaces.

Figure 4.2 shows an example of TESTSTEM output for ERBE (ERBS) input albedo and OLR. SW is shortwave heat load, computed from albedo; Q is total heat load and T is computed temperature variation for a spherical satellite with 5400-second time constant. Depending on choice of direct solar value (S_{hot} or S_{cold}), TESTSTEM output in ERBE input mode can be used to estimate either hot or cold extreme conditions (but not both within the same program run).

Figures 4.3 and 4.4 show samples from two TESTSTEM program runs, one for hot case conditions (Figure 4.3) and one for cold case (Figure 4.4) with STEM program input for albedo and OLR. In these figures three pulses of albedo and OLR are simulated (at minimum and maximum solar zenith angle points in each orbit). In these figures, "Albedo Q" is shortwave heat load. Temperature variations in Figures 4.3 and 4.4 are for a satellite having a thermal time constant of 128-seconds.

Another form of TESTSTEM output is file TESTTDIS.TXT which contains cumulative distribution of temperature, either as calculated from STEM base value plus pulses or from ERBE-observed albedo and OLR. Cumulative distributions of hot-case and cold-case temperatures are illustrated in Figure 4.5. This figure shows that non-critical albedo and OLR values reproduce ERBE observations over a one-month time period fairly well. As appropriate for mission-critical cases and mission-lifetime statistics, the mission-critical values exceed ERBE one-month observations on both hot and cold sides.

A synopsis and further interpretation of STEM and TESTSTEM results, compared with results from direct calculation from ERBE time series albedo and OLR, is provided in Section 5.1 (Figure 5.1).

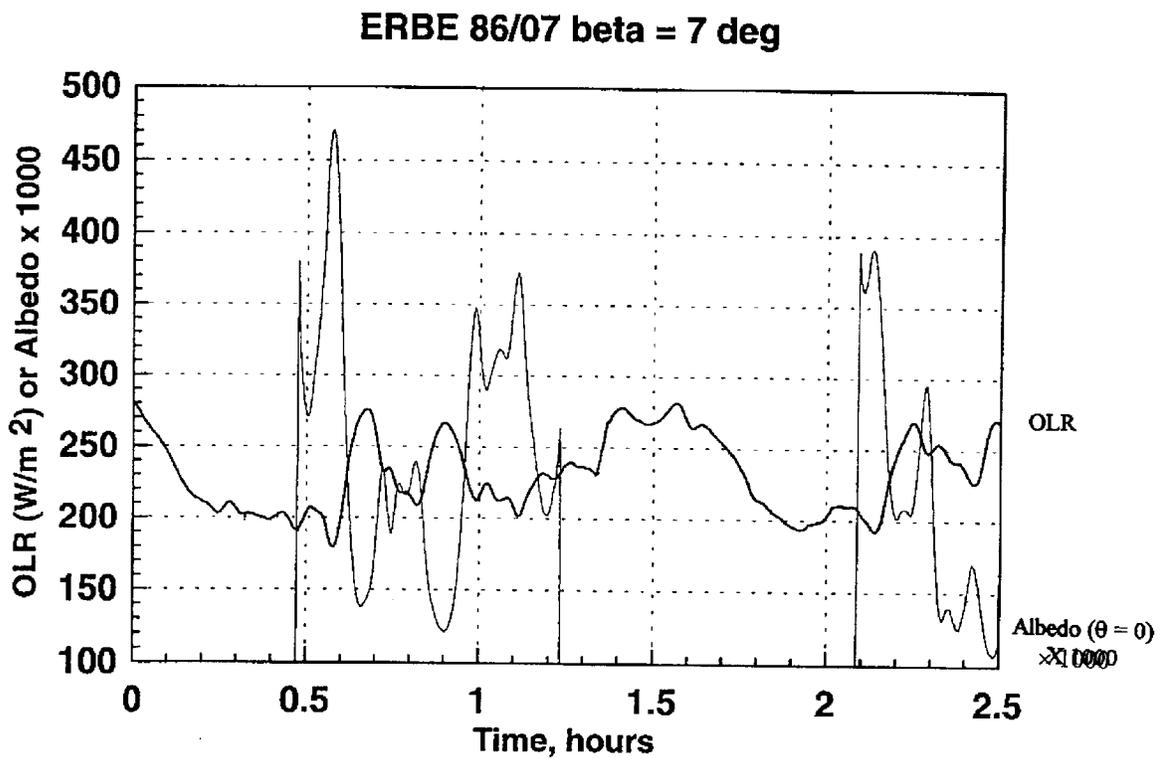


Figure 4.1 ERBE (ERBS) sample observed time series OLR (W/m²) and TOA albedo (× 1000, at solar zenith angle 0).

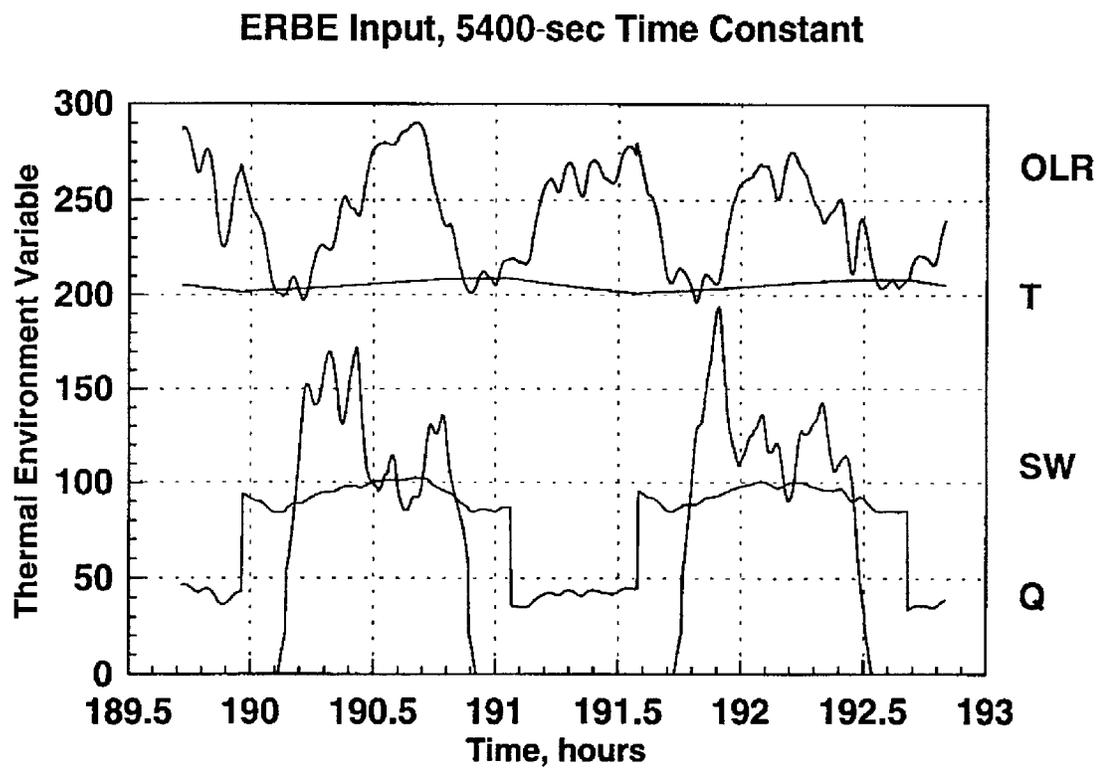


Figure 4.2 Sample TESTSTEM time series output, using observed ERBE (ERBS) albedo and OLR (W/m^2) as input.

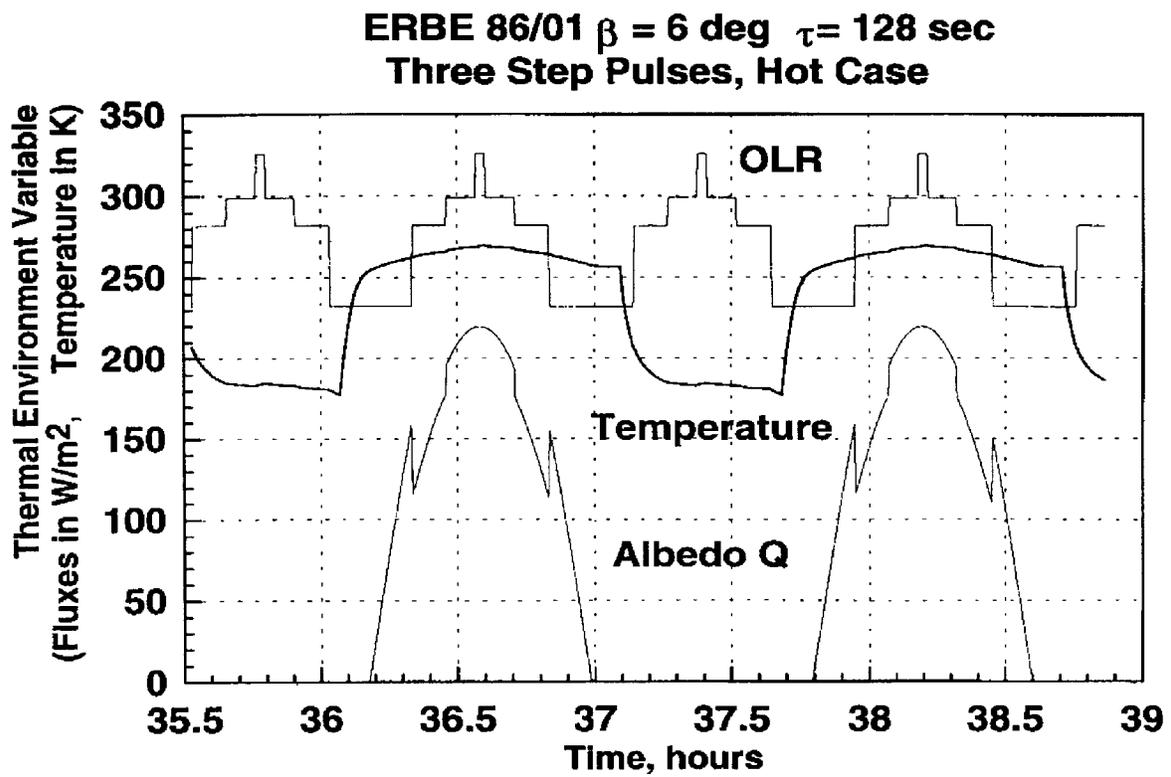


Figure 4.3 Sample TESTSTEM time series output, using input from STEM-derived, OLR extreme type, hot albedo and OLR (W/m^2).

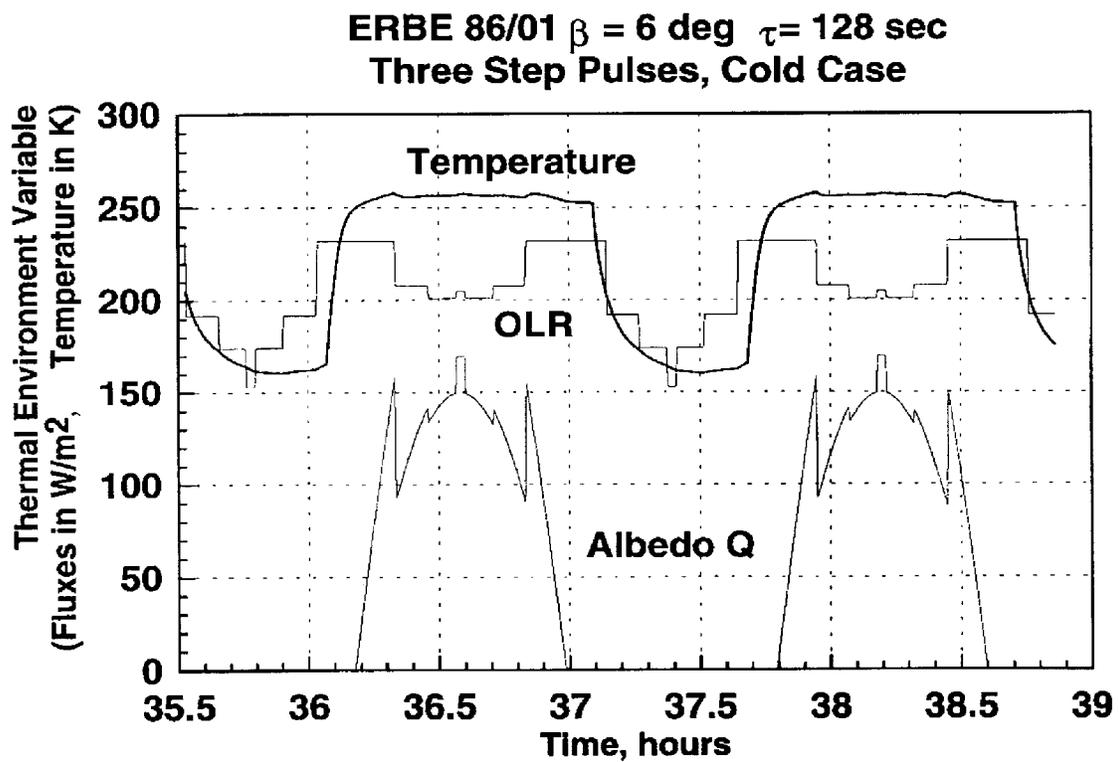


Figure 4.4 Sample TESTSTEM time series output, using input from STEM-derived, combined extreme type, cold albedo and OLR (W/m^2).

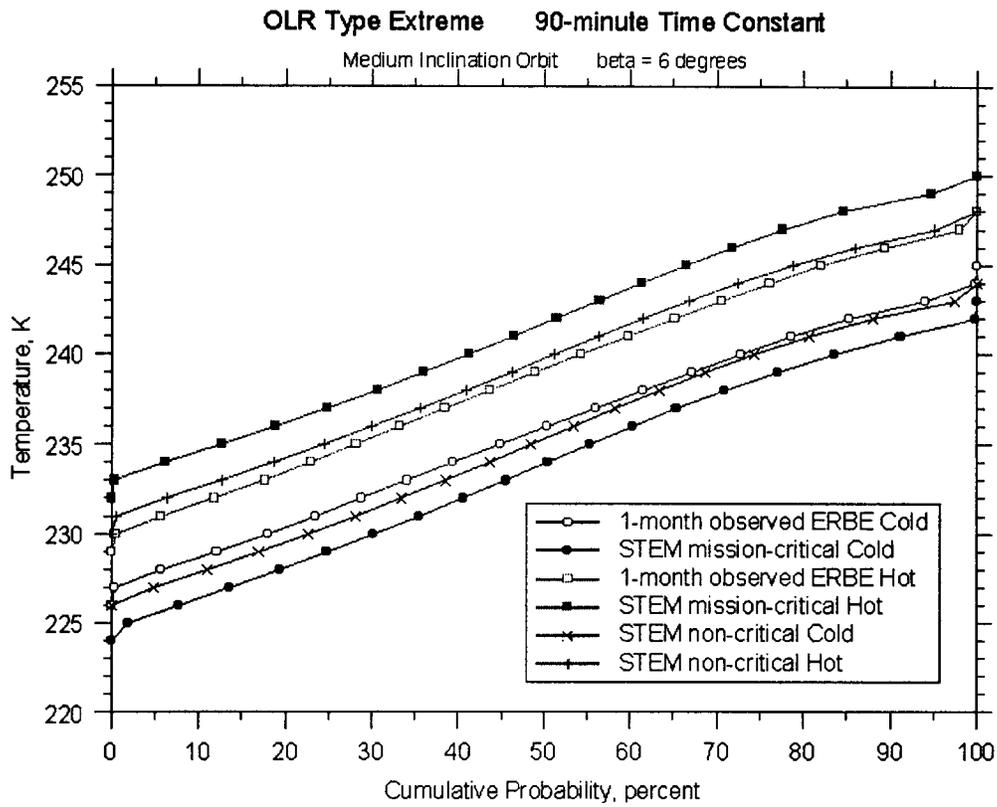


Figure 4.5 Cumulative distribution of temperatures computed by TESTSTEM for example case, and observed by ERBE for this case.

5. Conclusions And Frequently Asked Questions

5.1 Conclusions

STEM, together with its companion program TESTSTEM for testing and analyzing STEM output, offers a comprehensive and systematic method to estimate hot and cold extreme values of albedo and OLR to be used in specification of thermal environments for Earth-orbiting satellites. The purpose of STEM is to provide albedo and OLR values for use in thermal analyses; the purpose of TESTSTEM is to test sensitivity to choices in STEM output albedo and OLR options. In its sensitivity testing, TESTSTEM does a simplified thermal analysis on a hypothetical, simplified satellite system. However, TESTSTEM analysis is not intended to be a replacement for full-fledged thermal analysis of a (potentially complex) satellite system.

Data from several TESTSTEM program runs, using either ERBE (ERBS) time-series input for albedo and OLR, or multiple pulse STEM output, are plotted in Figure 5.1. This figure verifies that STEM-estimated hot and cold extreme albedo and OLR values produce extreme hot and cold temperatures (ordinate values in Figure 5.1) that agree well with temperature computed by TESTSTEM from ERBS input albedo and OLR (abscissa values in Figure 5.1). Data in this figure verify that STEM-suggested albedo and OLR extreme values should provide realistic and accurate specifications for thermal environment parameters for Earth-orbiting satellites under a variety of conditions.

The ability of STEM to provide albedo and OLR values for simulating pulses of environmental heat load is an important feature of the model. Design hot and cold conditions are frequently specified in terms of short-period variations in environmental heat load. See, for example, NASA and Russian Space Agency (1994) Table XII and Figures 4.3.2.6.11-3 and -4.

The goal to build satellites “cheaper, better, faster” is resulting in systems with more light weight, short-time-constant components. Weight savings achieved by providing less thermal shielding of these components would help to attain these goals. Both of these factors make it more important to simulate accurately the temperature response of systems having a variety of thermal time constants. This capability is an important feature of the STEM/TESTSTEM programs.

5.2 Frequently Asked Questions

1. The averaging time (thermal time constant) I want to use is not one of those built into STEM. What do I do?

It is not necessary to have an extremely close match-up between time constants and STEM averaging times (Section 2.3.3). When simulating albedo/OLR pulses, it is important to use a pulse duration that is next longest to the time constant for that system

component which has the shortest time constant (Section 3.3.4). If the analyst wants to test sensitivity to pulse duration, the next longer pulse duration beyond that may be run and compared.

2. How are thermal time constant and averaging time related? Does one equal the other?

Thermal time constant is a property of the system (computed by Equation 2.7). Averaging time is the length of time over which the ERBE albedo and OLR values have been averaged for use in STEM and TESTSTEM. Available averaging times are 24 hours (86400 sec), 6 hours (21600 sec), 90 minutes (5400 sec), 15 minutes (1800 sec), and 896, 128, and 16 seconds). These are related due to the fact that the analyst should select statistics from an averaging time that is approximately equal to or somewhat longer than the thermal time constant of the system. See discussion of sample cases in Section 3.3.4.

3. Why is STEM called a “simple” model? It looks pretty complicated to me. All I really want is one number for hot extreme and one for cold extreme.

If you know your system has only one range of time constants, you may be able to (manually) select one set of values from Table 2.3 or 2.4 (using appropriate orbital inclination). Cases 1 and 2 in section 3.3.4 provide information about this. However, to use this manual selection and get values that STEM produces, you must apply the orbital average zenith angle correction to the albedo value (Table 2.1 for particular beta angle). If your system has a high α/ϵ ratio, select albedo type extreme hot and cold cases. If it has a low α/ϵ ratio, select OLR type extreme hot and cold cases (Section 3.3.5). Of course the STEM program takes care of all of this for you: merely select the “Base @ Time Const” values. If your system has a wide range of thermal time constant values, it is not advisable to use single albedo and OLR values from Table 2.3. A combination of base values and pulse values should be used in this case. However, again STEM provides necessary guidance on which values to use and applies all necessary corrections (such as albedo correction for orbital average zenith angle).

4. I want to use albedo and OLR pulse(s) in my simulation. How do I select which pulse duration(s) to use?

The most likely choice of pulse length is the one just longer than the shortest time constant for a system component that is critical to your analysis. In the examples of Sections 3 and 4, the shortest time constant is ≈ 400 seconds, so a pulse of 896 seconds (shortest pulse longer than 400 seconds) would be the likely single choice. Some testing (with TESTSTEM) would be in order, however. Other cases to test would be: (1) a single pulse of 1800 seconds (somewhat longer; may allow system components to more nearly equilibrate thermally), (2) multiple pulses of 896 and 1800 seconds, (3) multiple pulses of 128, 896, and 1800 seconds (i.e. bracketing averaging times that are just shorter and just

longer than the relevant time constant of ≈ 400 seconds). TESTSTEM provides a quick and easy way to do such sensitivity analyses without requiring complex full fledged thermal analysis runs.

5. Does STEM output include the albedo correction or does the user have to apply it?

STEM output (Table 3.2) includes albedo corrections. Uncorrected values are in Table 2.3 or 2.4. As discussed in Section 3.3.3, correction $\langle c(\theta) \rangle$ (average solar zenith angle) is applied automatically to the “Base” values; correction $c(\beta)$ (minimum solar zenith angle) is applied automatically to the “Pulse” values. Amounts of applied correction are listed as “Avg, Min.za Albedo correction applied”, in the third line of STEM output.

6. The satellite system I am designing has complicated geometry (e.g. shading of one component by others, reflection or emissions from other components, etc.). STEM and TESTSTEM only treat a simple spherical satellite system. Is this good enough?

STEM and TESTSTEM are aids in selecting appropriate environmental parameters (albedo and OLR) to use in thermal analysis. They do not replace required thermal analysis using a thermal heat load program that treats complex satellite geometry. The purpose of STEM/TESTSTEM is to provide the best (most appropriate) estimate of albedo and OLR values to use in detailed thermal analyses, not to estimate realistic temperatures for components of systems with complex geometry. Figure 5.1 provides justification that STEM/TESTSTEM does this well. For an infrequently shaded component, albedo and OLR values estimated by STEM should be appropriate. For system components always shaded from Earth radiation it matters not what albedo and OLR are used, since Earth-reflected and Earth-emitted radiation components play a minor role in their thermal environment. For system components frequently or always shaded from direct sunlight, but not from Earth radiation, STEM albedo and OLR should still be appropriate because selection of hot and cold extremes is based on environmental heat load, not total heat load (Section 3.1.3). For cases identified as OLR type extreme, but with components which have significant shortwave radiation reflected from adjacent satellite components, the analyst may also want to examine albedo type extremes as an alternate (e.g. set STEM input parameter hotcase to 1). Similarly, for cases identified as albedo type extremes, but with significant re-radiated longwave from adjacent satellite components, the analyst may want to examine OLR type extremes (e.g. set STEM input parameter hotcase to 3).

7. What about special orientations (e.g., Earth-facing or space-looking system components)?

For a space-looking system not viewing Earth, it does not matter what albedo and OLR values are used. They have no appreciable effect on heat balance of these components. Earth-reflected and Earth-emitted radiation strongly affect the spherical

satellite assumed in STEM/TESTSTEM. Therefore albedo and OLR values suggested by this analysis should be appropriate for Earth-facing components.

8. ERBE satellites are in low Earth orbit (LEO). What about albedo and OLR values for a satellite in middle-altitude Earth orbit (MEO), in geosynchronous Earth orbit (GEO) or other high-altitude orbit?

The farther away from Earth a satellite is, the less important it is to have precise values for top-of-atmosphere (TOA) albedo and OLR. This effect and other aspects of GEO and other high altitude orbits are discussed in Chapter II of Gilmore (1994). For MEO cases, make sure, that the thermal analysis program used does appropriate adjustment from TOA to on-orbit conditions (e.g., by applying radial correction factors, Equations 3.4 and 3.5). STEM output values are for TOA conditions.

9. Why did you use such strange materials in the examples (Tables 3.2, 3.3, 4.1, and 4.3)? These are not common thermal control coating materials.

Example materials were chosen for two reasons: (1) Precisely because they are not common thermal control coating materials, the reader will not be tempted to try to avoid learning how to use STEM (and TESTSTEM) by using values from the sample tables in this report, (2) The samples, all being aluminum, but with three different surface conditions, remind the user that exposure to environmental conditions (UV radiation, atomic oxygen, etc.) may alter thermal results by causing changes in material surface states that have significant impact on the material's absorptance, α , and emittance, ϵ . As part of the process of learning how to use STEM and TESTSTEM, the reader is invited to repeat the example calculations for α and ϵ values suitable for more common thermal coating materials. Suggested values are: Teflon (5 mil, silver backing): $\alpha = 0.08$, $\epsilon = 0.78$; Chemglaze A276 White Paint: $\alpha = 0.23$, $\epsilon = 0.88$; Kapton (0.08 mil, aluminum backing): $\alpha = 0.23$, $\epsilon = 0.24$; Vapor Deposited Gold: $\alpha = 0.19$, $\epsilon = 0.02$.

10. STEM output values for direct solar, albedo, and OLR do not agree completely with values from Anderson and Smith (1994), Tables 9-1 through 9-4. Why is this?

See Sections 1.2, 1.3.1, and 1.3.3 for discussion about minor differences between STEM and Anderson and Smith Table 9-1. Their Tables 9-2 (low inclination), 9-3 (medium inclination), and 9-4 (high inclination) differ somewhat from values in Table 2.3 in this report for the following reasons:

(1) Anderson and Smith give lowest (0.04 percent) and highest albedo regardless of OLR, and OLR regardless of albedo. Their tables are somewhat comparable to albedo values for albedo-type extremes and OLR values for OLR-type extremes, but do not provide information about OLR values for albedo-type extremes or albedo values for OLR-type extremes; neither do they give albedo and OLR for combined type extreme conditions.

(2) Different averaging schemes were used (overlapping, running means for Anderson and Smith, non-overlapping averages for STEM).

(3) Analysis for STEM results used only high-inclination (NOAA-9) satellite data for high- inclination results and only medium-inclination (ERBS) satellite data for medium-inclination results (inclination-corrected values from ERBS were used to simulate low-inclination results). Anderson and Smith used inclination-corrected values from both satellites for all inclinations.

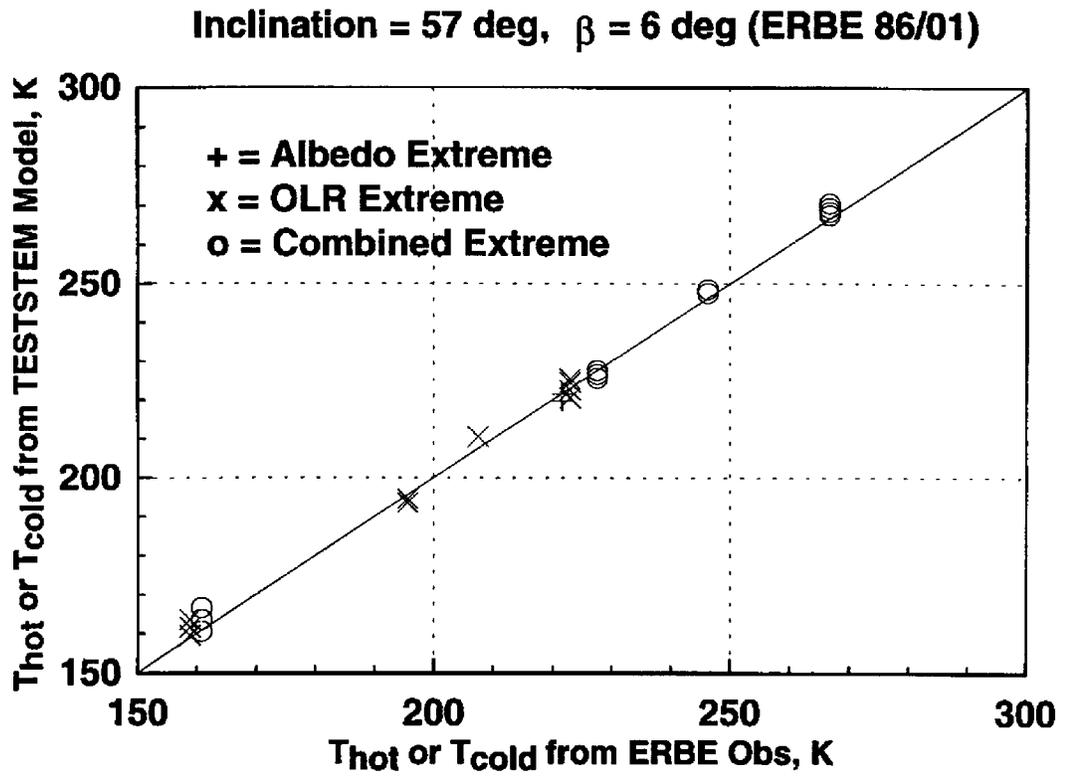


Figure 5.1 Maximum (Thot) and minimum (Tcold) temperatures, computed from TESTSTEM with STEM input (ordinate) and with ERBE (ERBS) input (abscissa).

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Appendix

How to Obtain STEM and TESTSTEM Programs

Qualified users may obtain a copy of STEM and TESTSTEM source code and required data files. The most convenient way to acquire this information is by file transfer protocol (ftp) from a UNIX computer (or other system with ftp capability). For details about ftp address and password contact

Dr. B. Jeffrey Anderson
Code ED44
NASA Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

phone: (256)-544-1661
e-mail: Jeff.Anderson@msfc.nasa.gov or

Dr. C. G. (Jere) Justus or Mr. Wade Batts
Code ED44/CSC
NASA Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

phone: (256)-544-3260 or (256)-544-9499
e-mail: Jere.Justus@msfc.nasa.gov or
Wade.Batts@msfc.nasa.gov

All files are ASCII format. Specific information about the files and instructions on how to execute the programs are contained in file

README.txt

(see also Sections 3 and 4 of this report).

The STEM program source code and required data files are the following:

stem.f	-	STEM program source code
stemin.std	-	sample NAMELIST format input file
stemout.std	-	reference STEM output from stemin.std input
tablemc.dat	-	table of mission-critical extreme albedo and OLR values (equivalent to Table 2.3 in this report).

tablenc.dat - table of non-critical extreme albedo and OLR values (equivalent to Table 2.4 in this report).

The TESTSTEM program source code and required data files are the following:

teststem.f - TESTSTEM program source code
testin.std - sample NAMELIST format input file
testout.std - reference TESTSTEM output from testin.std input

The following ERBE ERBS time series data files corrected to fill in data gaps and to provide a continuous time series are available. These files are named “ctsyyymm2.txt”, where yy is year and mm is month (2 denotes ERBS satellite). Available files are the following:

cts84112.txt	cts85022.txt	cts85042.txt	cts85072.txt
cts85102.txt	cts86012.txt	cts86032.txt	cts86052.txt
cts86062.txt	cts86072.txt	cts86082.txt	cts86042.txt
cts86112.txt			

At least one of these files is required for input of time series information to TESTSTEM. Some files are larger than one megabyte. If only a limited number of ERBS data files are desired, most appropriate ones are cts86012.txt with average beta angle 6 degrees, and cts86062.txt with average beta angle 77 degrees. These two files span the range of beta angles encountered by ERBS during the available data period.

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13. ABSTRACT (Maximum 200 words) This report presents a Simple Thermal Environment Model (STEM) for determining appropriate engineering design values to specify the thermal environment of Earth-orbiting satellites. The thermal environment of a satellite, consists of three components: (1) direct solar radiation, (2) Earth-atmosphere-reflected shortwave radiation, as characterized by Earth's albedo, and (3) Earth-atmosphere-emitted outgoing longwave radiation (OLR). This report, together with a companion "guidelines" report provides methodology and guidelines for selecting "design points" for thermal environment parameters for satellites and spacecraft systems. The methods and models reported here are outgrowths of Earth Radiation Budget Experiment (ERBE) satellite data analysis and thermal environment specifications discussed by Anderson and Smith (1994). In large part, this report is intended to update (and supersede) those results.				
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